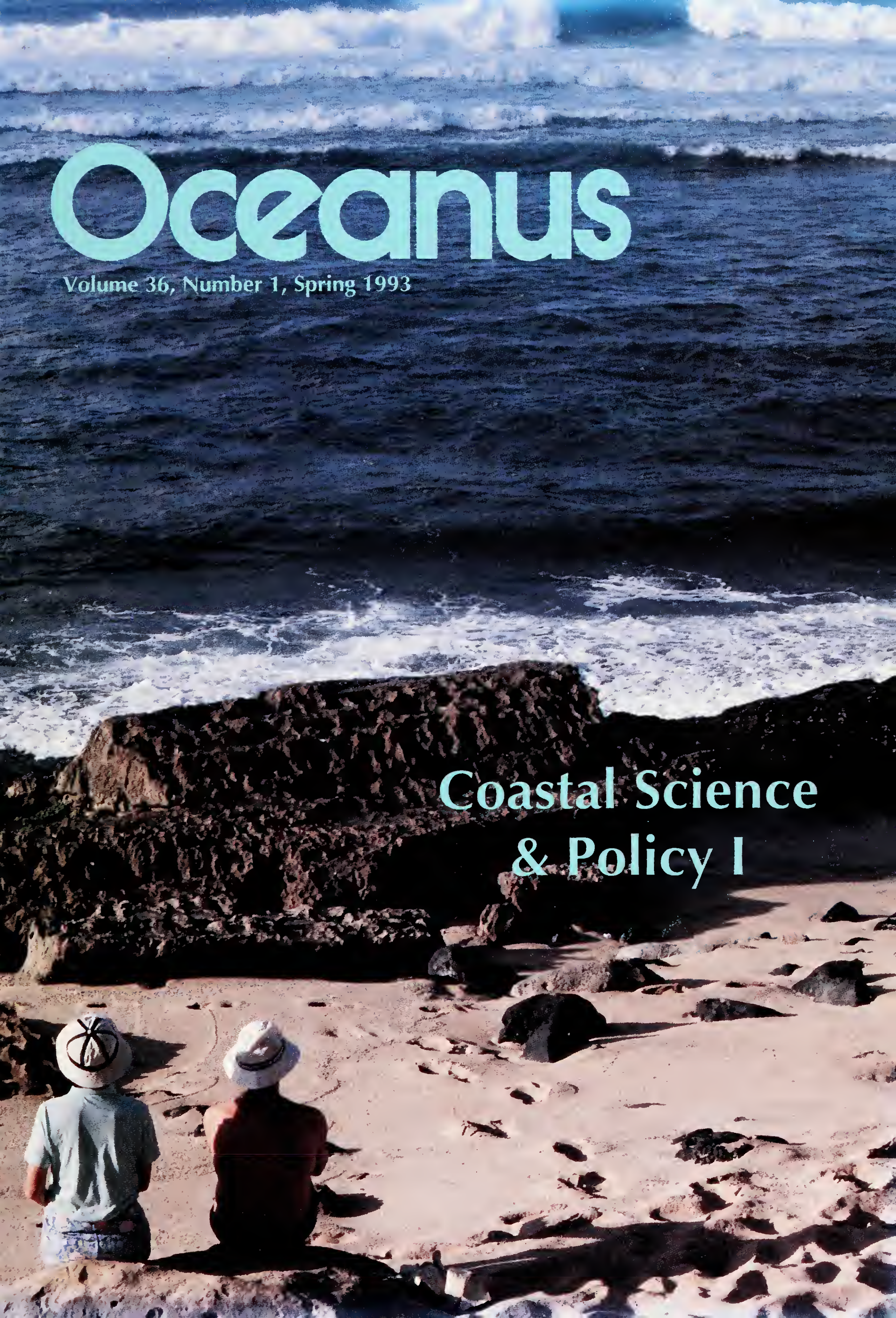
Oceanus

Volume 36, Number 1, Spring 1993



Coastal Science & Policy I

Our Coasts

Photos by Kelsey-Kennard Photographers, Inc.

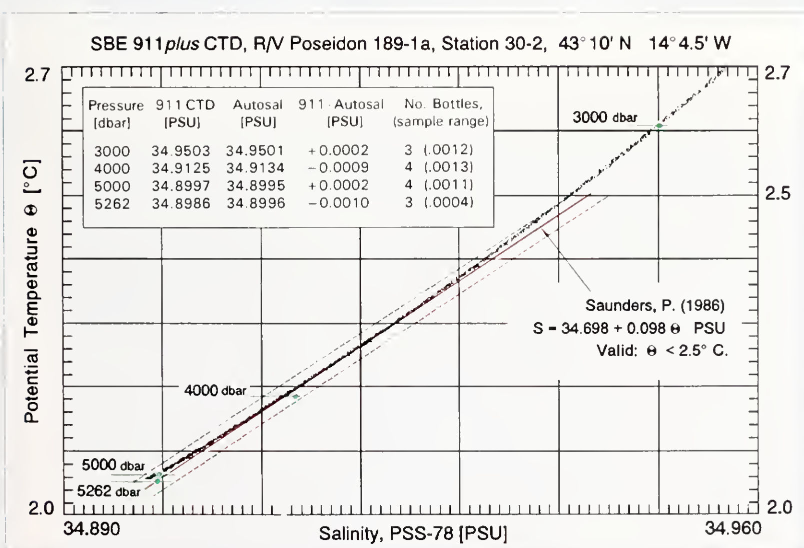
A naturally changing shoreline can threaten human habitation. At Chatham, Massachusetts, a nor'easter breached the barrier beach in 1987. When the photo above was taken in January 1988, one house opposite the breach had toppled. By November 1991, when the photo at left was taken, several houses (denoted by triangles) were completely gone. The circle indicates a structure to aid viewer orientation. Several articles in this issue of *Oceanus* discuss coastal crowding, and the National Flood Insurance Program is featured in "Ocean Law & Policy" on page 6.

Sea-Bird Wins in CTD Trials

In May 91 Canada's Bedford Institute of Oceanography performed comprehensive lab and at-sea comparisons of EG&G, Guildline, and Sea-Bird CTD systems. Bedford's conclusion that the Sea-Bird "has the intrinsic resolution and accuracy needed for WOCE-standard work" resulted in purchase of Sea-Bird 911*plus* CTD systems for their deep-ocean hydrographic program.

In similar trials conducted in January 1992 by Germany's Institut für Meereskunde/Kiel, our *911 plus CTD* again outperformed all other participating systems - including the EG&G Mark 5, NBIS Mark 3, and FSI Triton. The T-S plot below is representative of the superb results consistently obtained with the Sea-Bird CTD System during the IFM/Kiel intercomparison.

IFM/Kiel test results include overlaid down-and-up profile plots of *911 plus* data closely matching the historic Θ-S relationship in the N.E. Atlantic (Saunders, 1986, JPO, v.16(1)), and falling within the 0.002 PSU rms tolerance (dashed lines) of the Saunders parameterization. The 48-scan averages plotted below were obtained from raw 24 Hz full-rate data; there has been no editing, fitting, or post-correction of any kind. The data agree to within 0.001 PSU with averaged bottle values from 3000 to 5262 dbar (table and dots), and to better than 0.003 PSU with *every* bottle from 0 to 5262 dbar.



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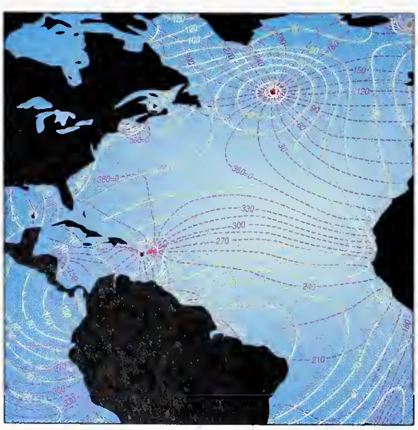
COASTAL SCIENCE & POLICY I

Creative Camera Concepts/Ned Manter

page 12

page 98

Jayne Doucette/WHOI Graphics



page 28

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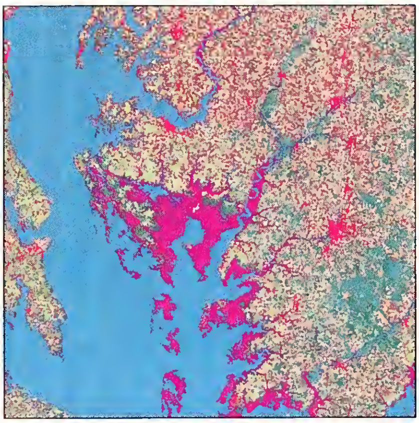
Headings and Readings

Massachusetts Water Resources Authority

page 61



NOAA/DOE/ORNL

page 88

Departments & Features

On the Cover: Beachcombers pause to take in the view of Maui, Hawaii. Photo by Cynthia R. Cronig.

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The National Flood Insurance Program

Beth Millemann

If the National Hurricane Center is right, the next 25 years could be the most deadly—and expensive—quarter century this country has ever seen. Scientists on the staff of the center, which is part of the National Oceanic and Atmospheric Administration (NOAA), predicted last April that the country was beginning a new storm cycle of "super hurricanes," noting that the new cycle comes on the heels of a relatively quiet storm period in the 1970s and 1980s. Those decades brought an explosion of coastal development that degraded coastal resources and placed millions of people, their structures, and taxpayer dollars at risk.

So far, the center's 25-year forecast has been eerily accurate:

- Last August, Hurricane Andrew slammed into Florida and Louisiana, causing dozens of deaths, massive fish kills, and other environmental damages, and claimed the title of the most expensive natural disaster ever to occur in the US—far outstripping the 1906 San Francisco earthquake and other acts of nature.
- In September 1992, Hurricane Iniki hit Hawaii, ravaged portions of the islands, causing millions of dollars worth of damage.
- In December 1992, a nor'easter, the area's worst storm in 20 years, pulverized the Atlantic coast from New Jersey to Massachusetts, causing major flooding and erosion, toppling shorefront houses, and breaking through portions of the barrier islands that form the Fire Island and Cape Cod National Seashores.
- In March, the Blizzard of 1993 pounded the eastern seaboard from Florida to Canada, leaving massive destruction and over 100 dead.

As storm waters receded from coastal towns and cities, a new flood poured into the affected areas: Millions of tax dollars were released through more than 50 federal programs that provide taxpayer dollars for coastal development and redevelopment. In fact, unless Congress acts to protect the federal treasury, the storms predicted by the National Hurricane Center will wreak havoc not only on shorefront property owners, but on federal taxpayers across the US.

The Grandaddy Coastal Development Subsidy: The National Flood Insurance Program

In 1968, Congress acted to end the cycle of development and redevelopment in flood-prone areas by creating the National Flood Insurance Program (NFIP). The idea was simple: Flood-prone communities could buy flood insurance that was otherwise unobtainable if, in exchange, they planned new development away from the hazardous water's edge. In this way, money would be generated through insurance sales to offset federal disaster relief payments for flood-prone buildings already in place, and, in the long run, new construction would be sited a safe distance from the water so that disaster relief would become less and less necessary. This would benefit the federal treasury, help save lives, and protect coastal

resources from the pollution and habitat loss caused by shorefront construction.

But it hasn't worked out that way. The National Flood Insurance Program is now one of the nation's largest domestic liabilities, right behind the Social Security system. It has roughly $210 billion worth of insurance in force, composed of about 2.5 million individual flood insurance policies. And instead of *discouraging* coastal development, more than three-quarters of the policies *insure* development along the marine and Great Lakes coasts. In fact, the Department of Interior concluded that federal development subsidies, like the National Flood Insurance Program, are one of two major factors that help make possible the explosion of development along the nation's shores.

Unfortunately, the boom of subsidized development may spell the bust of the federal taxpayer. Five years ago, the Federal Emergency Management Agency (FEMA), which directs the National Flood Insurance Program, calculated the probable program cost for a bad storm year. It's conclusion was sobering: Anywhere from $3.5 to $4 *billion* in federal flood insurance claims could be expected from just *one* catastrophic year of storms, hurricanes, and nor'easters. But a quick look at what's in the NFIP fund to pay the claims is even more sobering: The fund currently holds less than $400 *million*, roughly one-tenth of the probable price tag. What stands between a flood of insurance claims and the balance in the bank are the federal taxpayers.

Taxpayers have already bailed out the National Flood Insurance Program once. According to a report by the US General Accounting Office (GAO), the program operated from 1978 to 1987 at a $652 million deficit, which was made up by federal taxpayers. But what GAO didn't calculate was the cost to coastal resources that unwise shoreline development, underwritten by federal flood insurance, causes.

Polluted Waters and Destroyed Habitats

Experts estimate that 70 to 80 percent of coastal pollution is attributable to land-based sources. The explosion of coastal development over the past 25 years was paydirt to realtors and developers, but brought disaster to wildlife and fisheries that depend on clean, healthy coastal resources:

- Roughly 40 percent of the nation's shellfish beds are closed because of sewage discharges and nonpoint runoff from coastal towns and cities.
- Every year, 20,000 acres of coastal wetlands are lost, mostly to development. The Fish and Wildlife Service estimates that 75 percent of the nation's commercial fish species depend on coastal wetlands for survival. Every

Susan F. Witzell

Owners of this shorefront property in Falmouth, Massachusetts, were dismayed to find their home all but destroyed by Hurricane Bob in August of 1991.

lost wetland acre is further shrinkage of fish habitat, and the recreational and commercial fishing industries supported by that habitat.

• Dozens of endangered species, including birds, sea turtles, and marine mammals, depend on clean coastal waters and abundant habitat for their survival. Yet development annually gobbles up thousands of acres of the barrier islands, beaches, and coastal wetlands these animals call home.

Coastal development threatens to swallow up the very resources that draw us to the shore. Unless action is quickly taken, it may also overwhelm an equally scarce resource: federal tax dollars.

Reform of the National Flood Insurance Program

When Congress tried to overhaul the dangerously imbalanced Flood Insurance Program last year, it ran into a force as powerful as any hurricane: the National Association of Realtors and the National Association of Homebuilders, working in conjunction with a handful of well-placed coastal homeowners.

After four years of research, hearings, and investigations, in May 1991 the House of Representatives passed (by a vote of 388 to 18) a bill to reform the program. More than 100 conservation groups around the country supported the legislation, as did coastal state officials. The Office of Management and Budget declared that it would save $11 million in just four years.

A similar bill was introduced in the Senate by John Kerry (D-MA) in August. Several senators joined in support of the Kerry bill, including Alfonse D'Amato (R-NY).

The bill would have taken a common-sense approach to the problems plaguing the program. It would have denied federal flood insurance for new construction in eroding coastal and Great Lakes areas. This would have protected the program from insuring development that is most prone to hurricanes, storms, flooding, and erosion, and the costly damage these storms cause. The bill also would have provided money to make current structures less vulnerable to flooding, thereby decreasing expensive and repetitive claims.

But by early 1992, the tide began to turn against the legislation. Characterizing it as everything from a land-grab to a constitutional "taking" to forced relocation of property owners from the shore, the realtors and homebuilders mounted a national campaign against the bill. They realized that if they didn't have the federal taxpayer insuring hazard-area development, construction on the shore would become a more dangerous and less profitable enterprise. Acting on behalf of property owners on New York's Fire Island, the former supporter of the legislation, Senator D'Amato, became one of its chief opponents. The special-interest pressure became too much, and the legislation died in the Senate in the closing days of the last Congress.

Action at Last

Three notable events have occurred since the flood insurance legislation was killed last October. A new president was elected, a new Congress came to town, and the bills started pouring in from Hurricanes Andrew and Iniki, the dreadful December nor'easter, and the Blizzard of '93. Faced with a mounting federal deficit and a prognosis of 25 years of "super hurricanes," Congress may decide that now is the time for the Flood Insurance Program to do what it was created to do in 1968: encourage communities to guide new development away from the water's edge to save lives, money, and environmental resources. ✪

Beth Millemann is Executive Director of the Coast Alliance, a national environmental group headquartered in Washington, DC. She is the author of Storm on the Horizon: The National Flood Insurance Program and America's Coasts *(Coast Alliance: Washington, DC, 1989).*

An Introduction—

Perspectives from a Shrinking Globe

David G. Aubrey

With summer approaching, many of us are considering where to spend our summer vacations. The beach is a universal favorite for vacationers. As we contemplate our favorite beach retreats this year, we might ask ourselves a few questions: Is there more traffic going to the shore this year, and are the cities or suburbs growing faster than before? Isn't that new resort complex built on what used to be wild beach grass or sea oats? Why does the surf seem so much closer to the parking lot this year, and the sand narrower? Why are those hypodermic needles being tossed ashore by the waves? What happened to that marsh creek we used to hike at low tide, where we got aquainted with all the crabs and small fish? Why are fish dying and washing ashore today, along with that yellowish foam and blobs of oil?

Contemplating these scenes, we may realize we are experiencing firsthand some direct results of the conflicting uses of the coastal zone. Our continued encroachment upon the shore places increased demands on coastal resources. How we address these demands is part of the legacy we leave our children. As the globe continues to shrink and we recognize the interconnectedness of coastal problems around the world, we must think hard about this global legacy. How habitable or functional will our coastal waters be 20 years hence? Will we be any wiser in our use of coastal areas, or more sympathetic with the natural functions of the coastal zone? Are we on the way to resolving our waste-disposal problems, and what role will the ocean play in this resolution? Will policy options be understood and implemented regionally, or will individual nations continue to ignore the realities of the common heritage that is the sea?

This is the first of two sequential *Oceanus* issues that focus on the coastal zone's scientific aspects and its intertwined and difficult policy and management issues. Conflicting use is a recurrent theme, as transportation, waste disposal, recreation, habitation, energy usage, and mariculture all struggle for coastal-zone access. And what of the natural

ecosystem? What is its response to this crowding? How will the environment's decline affect the very habitat we are seeking to exploit? Common issues—difficult choices. Ed Goldberg explores some of these uses and their possible consequences. He notes some policy options in Europe that suggest we may be learning how to use our coastal areas more wisely.

Another recurrent theme is overdevelopment. Beth Millemann suggests that storms of the last 20 years have been benign, whereas the next 25 years may bring a cycle of "super-hurricanes" such as this past year's Andrew. John Williams and coauthors discuss Florida storms of the past century and their patterns through time, ending with a discussion of the most expensive US hurricane to date: Andrew. David Bush and Orrin Pilkey also focus on a difficult management decision: How to treat threats to the lighthouses of Cape Hatteras and Morris Island. These three articles discuss important aspects of coastal science and planning, questioning the best mix of policies and risk.

Wastewater management is a recurrent theme that is particularly topical in Massachusetts. The $6 billion Boston sewage treatment project is under continued scrutiny, as the already-high sewage rates promise to increase manyfold with the project nearing completion. Paul Levy describes the political conditions leading to the massive "big pipe" alternative, and Peter Shelley discusses the role of citizen groups in environmental issues. Dave Aubrey and Mike Connor discuss some of the big pipe controversies, from the perspectives of academic scientist and agency scientist. The exigencies of court orders and the limited duration of political lifetimes place interesting constraints on such a large project, and we discuss the role of scientific uncertainty in siting questions. Susan Peterson outlines some alternatives to the big pipe, including an interesting plea for decentralization of wastewater treatment toward more effective water management.

Scientific uncertainty plagues many coastal management decisions.

Scientific uncertainty plagues many coastal management decisions, as it does other societal problems. Because of the complex networks of interacting environmental components, scientists cannot predict exactly what will happen when a specific environmental button is pushed a certain distance. Scientists may be able to predict tendencies, but as the Boston Harbor outfall debate demonstrates, competing or offsetting biotic responses cannot always be assessed quantitatively. Clearly we need to improve our knowledge and reduce our uncertainties. Some of the scientific issues are addressed as Chris Garrett and Leo Maas discuss the orchestration of the tides, describing the dominant tones and underlying harmonics that give this music its richness and interest. Graham Giese and Dave Chapman then continue this spectral investigation by exploring a new class of coastal water motions previously unidentified, though known to contribute to this marine orchestral movement.

The issue is further rounded out with descriptions of two new programs to advance our scientific understanding of complex coastal systems, so we can manage them better and develop improved, enlightened policy options. Lauren Wenzel and Don Scavia elaborate on the National Oceanic and Atmospheric Association's Coastal Ocean Program and its focus on critical coastal zone management issues, while Ken Brink describes a program to examine Coastal Ocean Processes (CoOP) from an interdisciplinary, basic-science standpoint. Increased scientific

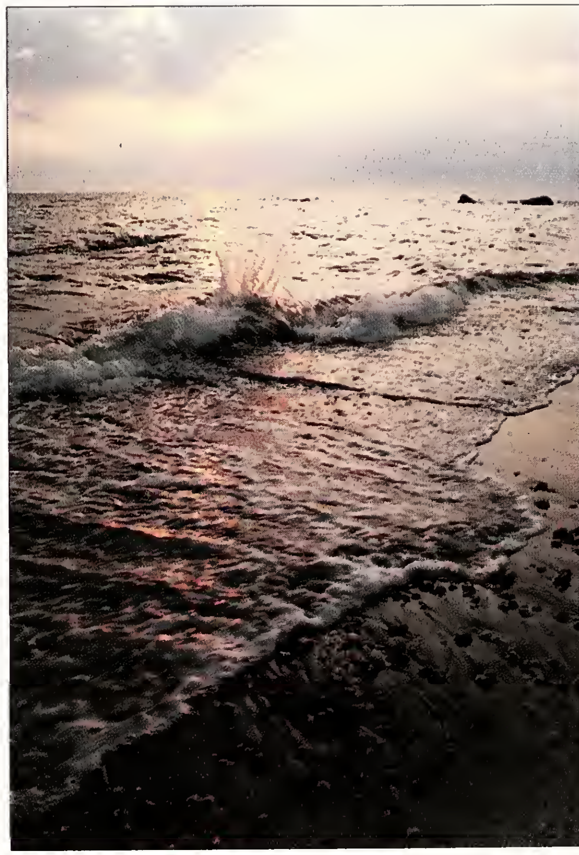
focus on the coastal zone by many state, national, and international groups requires strong coordination and insightful problem identification—a challenge for the future.

Several general recommendations emerge from this mix of papers.

• First, strong partnerships must be built between the academic community and mission agencies responsible for management and policy. Such partnering may require changes in perspective from both groups: a willingness to incorporate complex scientific results into management and policy decisions on the agencies' part, and a commitment from the scientists to communicate their results more effectively to those agencies. Partnerships will help break down the implicit conflict between these two groups, and foster improved interaction.

• Mechanisms to improve translation, interpretation, and integration of basic scientific research into mainstream agencies must be implemented. The tension that still exists between natural scientists and social scientists must be eased by massaging the links between the groups, to encourage greater and more effective communication.

• Finally, coastal issues are global, and the interconnectedness of coastal areas is real. The appropriate and varied roles of local, state, national, and international policy and science initiatives must be clarified and coordinated. Effective regional policy and management require scientists working at common levels, with common techniques and analysis procedures. Discussion of results must be open and frequent, and must include peer review to maintain high academic standards. These relative roles should be defined early, and form the basis for international or regional accords. ✪



Creative Camera Concepts/Ned Manter

Will this shoreline in West Falmouth, Massachusetts, look this inviting in 20 years?

David G. Aubrey is a Senior Scientist in the Department of Geology & Geophysics at Woods Hole Oceanographic Institution and former Director of the Institution's Coastal Research Center.

Editor's Note: Articles scheduled for the Coastal Science and Policy II issue include the status of fisheries (Michael Sissenwine), coastal pollution (Judy McDowell), the nutrient impact on various coastal systems (Scott Nixon), rivers and estuaries (Chuck Nittrouer and William Boicourt, respectively), and a profile on David Packard and Julie Packard (Nora Deans).

Competitors for Coastal Ocean Space

Edward D. Goldberg

Ever-increasing populations stress both the land and water environments of the coastal zone.

Many factors contribute to coastal-zone space conflicts. First, the occupants, uses, and constructions of the world's 440,000-kilometer coastline continually change in response to economic and social pressures. Second, the ever-increasing populations stress both the land and water environments of the coastal zone. Finally, the early-1990s de-emphasis of military operations will open up space presently occupied by armies and navies in many countries.

Demographics

There is a marked movement of people primarily from low latitudes to higher-latitude coastal zones, in search of a better life through improvements in work opportunities, home environments, medical facilities, and educational systems. This movement is occurring in many regions—from southern to northern Mediterranean countries, from Mexico and Guatemala to California, from Haiti and Cuba to Florida, and from the Bahia region to the Rio Grande region in Brazil. The immigrants often tax host-area facilities, and government infrastructures have difficulty coping with the unregulated influx. (One option to mitigate this problem would be to make the inland noncoastal zone areas more attractive to the migrating peoples.)

Entry of differing-ethnicity migrants can create discomfort for host populations. For example, Italy has been flooded in the last several years by a million immigrants from Africa, Asia, and eastern Europe. Until this time, Italy had remarkably liberal immigration policies and intended to create a multiracial society. Laws limiting immigration were initially proposed in March 1990, and 75 percent of Italian citizens now favor closing the border to all new immigration. The recently arrived migrants exacerbated an already serious unemployment problem, were perceived as being purveyors of crime, disease, and drugs, and were very evident by their appearance. Often out of work and without housing, they flooded the Italian beaches. As the relevant governmental agencies have been unable to cope, an immigration moratorium may provide a breathing period to alleviate the situation. Immigrants constitute strong competition for coastal space in many parts of the world.

The most detailed demographic studies have been made in the Mediterranean and US coastal areas by the United Nations Environment Programme and the US National Oceanic and Atmospheric Administration, respectively.

Tourism and Recreation

Tourism is probably the world's largest single industry, accounting for at least 5 percent of the combined gross national products (GNPs). The coastal zone is a major attraction, drawing about half of all national and international travelers. The heightened expectation of the world citizenry to roam, coupled with increased leisure time and financial resources, will continue to spark this activity.

The economies of many countries in the developing world, especially the small island nations, are based on continuous, growing tourism. For example, the Caribbean Islands, to a large extent, support their economies with tourist revenues that have steadily risen during the past decade. Hotel, restaurant, shop-sale, tour, and native-performance revenues contribute about 43 percent of the region's combined gross national products. In 1987, 5.6 million cruise passengers visited the Caribbean. Overall, world cruise populations are increasing at a double-digit rate.

Availability of seafood (a favorite of the visitors) and a healthy marine environment that accommodates many forms of recreation are crucial to the success of tourism in many developing countries. These factors are sometimes challenged by inadequate waste disposal that allows continual entry of toxic pathogens and chemicals to coastal waters. These flows, with potential threats to human health both through seafood ingestion and through direct exposure, have clear, undesirable consequences. Yet the cost of upgrading sewage systems is formidable to small nations with a host of other expensive social problems.

Creative Camera Concepts/Ned Manter

The port city of Boston with its tall buildings and the sailboats on its harbor illustrates the coastal zone's many human uses.

In the developed world, the strong financial position of the tourist and recreation industries have established them as primary contestants in battles over coastal-ocean space. Construction of hotels, recreation areas, shops, and restaurants that appeal to tourists creates a most unusual seascape.

An alternative use of seacoast areas abandoned by the military might be establishment of marine parks to enhance the lives of residents and visitors and to protect regional ecology. This use would not only support tourism, but could also offer unique research facilities and maintain an important heritage. Marine parks can take many forms: fishing reserves, diving areas, and natural marine reserves that have cultural, scientific, and aesthetic components.

Many such areas have been developed in the Mediterranean with the support of the European Council. France has the most extensive program, with 16 areas designated for special types of care. Greece has established three marine parks for the protection of monk seals and marine turtles. Other countries with active programs include Israel, Italy, Egypt, Tunisia, and Spain. (The Fall 1993 *Oceanus* will feature marine protected areas.)

Mariculture

Mariculture production can disturb the quality of the coastal environment.

Fish, shellfish, and algae farming usually damage the physical appearance and the quality of coastal-zone waters, but make significant economic contributions to some nations and fortify diets around the world. Fresh- and saltwater aquaculture accounts for about 10 percent of the world fish and shellfish harvest. It is dominated by freshwater finfish culture, but marine activities are clearly increasing. Worldwide crustacean cultivation increased nearly tenfold between 1975 and 1985; the price of shrimp correspondingly decreased 25 percent.

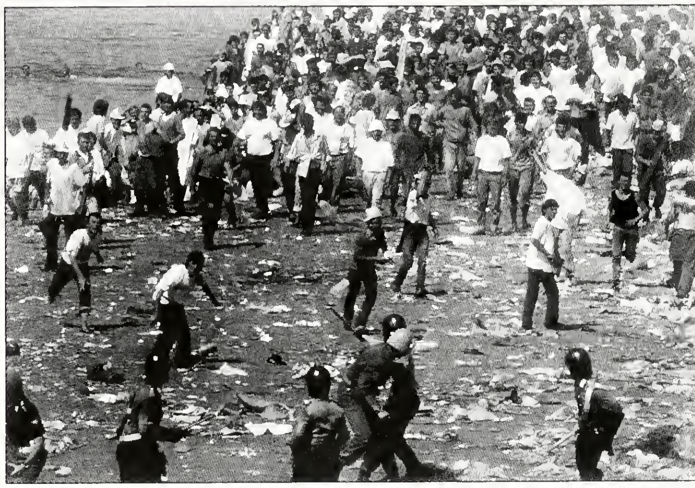
Demands for protein, coupled with technical improvements in aquaculture and the decreasing availability of fish in the wild, clearly will advance mariculture in the coastal zone. For example, genetic engineering promises to increase the efficiency of fish farming in the very near future. In a mid-1980s investigation, fish fed synthetic growth hormones gained twice as much weight as fish in control groups. Though economics were against implementing this approach on a commercial basis (the synthetic hormones were expensive, and their uptake efficiency was low), the research continues and may give aquaculture an additional boost.

Four types of mariculture are dominant: seaweed, shrimp, mussel, and salmon. Of these, shrimp have become one of the most valuable. In 1989, 26 percent of the world's shrimp supply came from farming, with a harvest of 565,000 tons. Asia is the largest producer, followed by South America. The producing countries utilize about 15 percent of the crop, and the remainder is exported to the US, Japan, and Europe.

Mariculture production can disturb the quality of the coastal environment. The pens themselves can be aesthetically unpleasant. Natural habitats are lost, such as the mangrove forests—a valuable but declining ecosystem—that are being displaced by shrimp farming in the southeast Pacific and Central and South America. But the creation of anoxic environments is perhaps more important. Fish farming in cages produces organic residues from uneaten food and metabolic wastes. The materials sink to the bottom, and through microbial decomposition release dissolved nutrients such as phosphate, nitrate, silicate, and ammonia. Enhanced algal growth in the water column can follow and serious pollution problems can develop. Hong Kong Island, for example, has degraded environments under cages located in waters that were once considered clean and beautiful. This situation outrages another competitor for this coastal space, the Hong Kong Yachting Association, which represents user communities that want to use the waters for boating, windsurfing, swimming, and diving. Mariculture accounts for 50 percent of Hong Kong's total fresh-fish consumption and has an annual value of $25 million, which is probably comparable to the Yacht Club's cash flow.

Waste Space

A weak contender today for coastal-ocean space is domestic and industrial waste accommodation. Over the past several decades, environmental groups and regulatory agencies in the developed world have been effective in creating the perception that marine systems cannot accommodate societal discards without resource loss. On the other hand, social and natural scientists and engineers have shown that comparisons of disposal options (air, sea, and land) for a specific waste in a particular region do not exclude the ocean and, in fact, in some cases favor it.



Baldelli/Contrasto/SABA

In late summer of 1991, more than 18,000 Albanian refugees confronted Italian police on the docks at Bari.

But these arguments will pale in the face of future economic forces. Land available for waste disposal is running out near populated areas, especially those along the coasts. In the US, domestic wastes are shipped across state boundaries, for example, from New York and New Jersey to Pennsylvania and Ohio. For hazardous wastes, the situation is even more pressing. California's stringent regulations on hazardous-waste disposal (compared to federal restrictions) have driven in-state disposal costs to a range of \$261 to \$1,011 per ton. On the other hand, wastes can be transported to other states, such as Utah, for disposal at about \$142 per ton. This is changing, however. Utah and other states that receive California's toxic wastes are reacting both by restricting the amounts they are willing to take and by proposing increased fees.

A return to ocean-waste disposal is likely as scientific and engineering judgments dominate the policy decision processes and displace perceptions that are often emotionally based. When the economic, social, scientific, and engineering aspects of land and air (incineration) disposal are dispassionately compared with those of coastal-ocean disposal, a rejuvenated competitor for coastal-ocean space will most likely appear.

Transportation

Improved and expanded harbor facilities for increasing transoceanic world trade comprise another contender for coastal-zone space. As the rising world population demands more materials and energy to achieve higher standards of living, countries that produce or import high-volume, low-cost commodities, such as coal, oil, timber, and grain, may employ large, ocean-traversing carriers (150,000 dead-weight tons or more) that at present primarily transport petroleum and petroleum products. For example, shifting Mediterranean industrialization from northern to southern and eastern countries will create a need for improved harbor facilities. Steel production in northern Europe will probably decrease in the near future as a consequence of competition from the outside. As part of their industrialization, southern and eastern

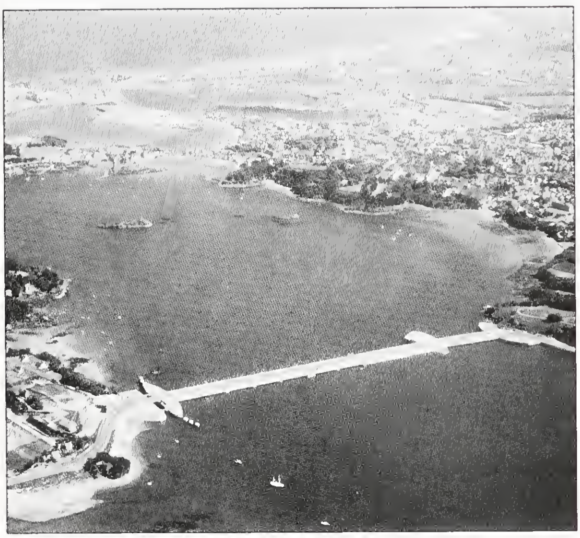
Mediterranean countries will begin to import iron ore and coal, and large vessels will probably be employed where there are appropriate ship and cargo-handling facilities.

Harbor improvement for handling the larger vessels usually consists of deepening channels through extensive and continuous dredging, which alters life processes in and surrounding the port area; for example, fishing and fish-nursery grounds may be changed or eliminated. The dredging itself can interfere with sediment-transport processes. Finally, increased ship loading and unloading can place additional stresses upon space in the port vicinity through the entry of alien materials and nonindigenous organisms to the waters.

Some Other Competitors

In addition to these contenders for coastal-ocean space, there are some minor competitors from the mining, energy, and fishing industries. Today all have potential, but none loom as serious challengers.

Energy. The continuous recovery of energy from the sea remains elusive although it is often discussed in the popular media. The economics of constructing appropriate structures are formidable. Still, advocates of the various possible schemes remain committed. They are especially encouraged by the argument that the three promising technologies, ocean thermal, tidal, and wave energy conversions, do not contribute greenhouse gases to the environment.



Michel Brigaud/French Embassy

The Rance Tidal Power Station, on the Rance River in Brittany, France, is the only successfully operating plant that harnesses tidal energy. Some 30 sites worldwide have the potential for tidal energy production, but the necessary construction is very expensive.

The most notorious of these, ocean thermal energy conversion (OTEC), utilizes the temperature difference between warm surface and cold deep waters to run a turbine in closed or open cycles. The plausible geographical zone for OTEC centers on the equator and extends north and south by about 20° latitude. Only three developed nations are within this belt: Australia, Japan, and the US. A basic requirement to bring OTEC into serious competition for coastal-ocean space is the construction of a successful prototype in the range of 1 to 50 megawatts.

Energy can be drawn from ocean tides generated by gravitational forces exerted by the moon and the sun upon the earth. A straightforward way to harness this tidal energy involves placing a barrier with sluices and turbines across a marine basin. The appropriate coupling of tidal forces with basin geometry limits power generation to between 50° and 60° latitude. The only successful operating plant, which was completed in 1967 at the mouth of the river Rance in Brittany, produces 240,000 watts. Smaller plants have been built in China, Canada, and the former Soviet Union. There are probably 30 sites in the world that could be successfully employed for tidal energy.

Many ideas for harnessing wave energy have been proposed, but today most devices involve compressing air to run a turbine connected to a generator. Japan and Norway, which have successfully demonstrated pilot models, appear to be at the forefront of wave-energy activity, with the UK not far behind.

Fishing. The commercial fishing industry's needs for US coastal-ocean space have decreased over the past decade. Although demand for marine food products has been rising, a number of factors combine to lessen the requirements for support facilities in harbor areas. First, changes in fishing techniques as small fishing boats are replaced by large catcher/processor vessels create a need for different types of port space. Second, mariculture products are competing successfully with wild-caught marine food, and mariculture production is increasing annually. Finally, the productivity of some existing fisheries is being diminished by physical alteration of estuaries and wetlands, which reduces breeding areas and nursery grounds. (See also "Helping a Diminished Industry" on page 89.)

Mining. Of the solid minerals extracted from the marine environment, the two most important groups are sea salt for use as a condiment and as an industrial chemical, and sand and gravel for use in concrete production, beach replenishment, roadfill, landfill, and artificial-island construction. In addition, there are placer minerals that have been beneficiated from the sediments, including gold, titanium oxides, phosphites, and chromites. The largest coastal sand and gravel exploitation takes place in Japan and Great Britain, but the needs of all countries are increasing. This mining can impact fish nursery and breeding grounds. Further, these activities interfere with erosional processes and the integrity of submarine cables and oil and gas pipelines.

Sand and gravel resources from the sea compete with their land-based counterparts. Distances from the quarry site to the use site are ever-increasing in developed areas. The relative transport costs of land- and sea-derived sand and gravel, coupled with the qualities of the materials, will largely determine which will have the competitive advantage. In some cases the rental of shore space for marine activities will enter the financial picture.

A New Direction for Coastal Ocean Space

In this last decade of the 20th century, social and political changes are reordering priorities for coastal-zone space utilization in many eastern European countries. Military activities with their associated space needs are on the downswing. In the 1970s and 1980s, military uses, and engineering research to support them, were given the highest priorities for coastal-ocean space. These were followed by bioresource utilization to satisfy the increasing need for animal protein. Recreation, tourism, and environmental protection had the lowest priorities. As social and economic patterns stabilize, tourist-related activities that can attract hard currencies from the west will increase, and tourism could become the most important coastal-space occupant in these countries.

Social and political changes are reordering priorities for coastal-zone space utilization in many eastern European countries.

The Discontented Locals

Over the past several centuries, citizens of the developed world have been acquiring coastal-zone space in the developing world for additional habitat, recreation, and for the profitable activities previously discussed. Resentment can build up among local people as they see a valuable part of their homeland exploited by outsiders and sometimes made unavailable to them. Stresses can develop among all concerned.

Peter Rothholz Associates, Inc.

Natives of Bathsheba, on the east coast of Barbados, still enjoy a vista relatively unchanged by major development.

Such has been the case in Barbados. In the past, shipping, fishing, some agriculture, and small-boat construction occupied the coastal zone. These uses have been challenged by, and in some cases lost to, tourism. Over the past 25 years or so, the west side of Barbados, with a nearly 150-kilometer coastline, has become the site for major hotel development, primarily for the winter season. Part of the shoreline has been beautified by the development of beaches. However, other beaches have been destroyed and reduced to coral rubble. Pollution from domestic wastes threatens the reefs and swimmers. Public beach access has been minimized through resort construction. Fishing boats have gone. Land prices have skyrocketed and land purchases are no longer readily available to the native population.

The unaffected northeastern part of the island contrasts with the tourist areas near the major city, Bridgetown, to the west, and the airport to the southeast. Natives can still enjoy a relatively unaffected east coast, albeit with its somewhat less-desirable climate, but this is perhaps some compensation to the local citizens who benefit from tourist contributions to the economy.

Demands for coastal space will clearly exceed what is available. Besides tourism and recreation, mariculture, habitat, waste space, transportation, and the lingering military, there are some minor players: energy development such as tidal power and ocean thermal energy conversion (OTEC), coastal mining—especially sand and gravel, and the declining fishing industry. All have their government patrons. If the past is a guide to the future, the scientific and engineering communities will have but a small say in the allocation of any available coastal space. Economics and social pressures will prevail. Still, guidance from scholars may help to maintain and improve coastal-zone quality.

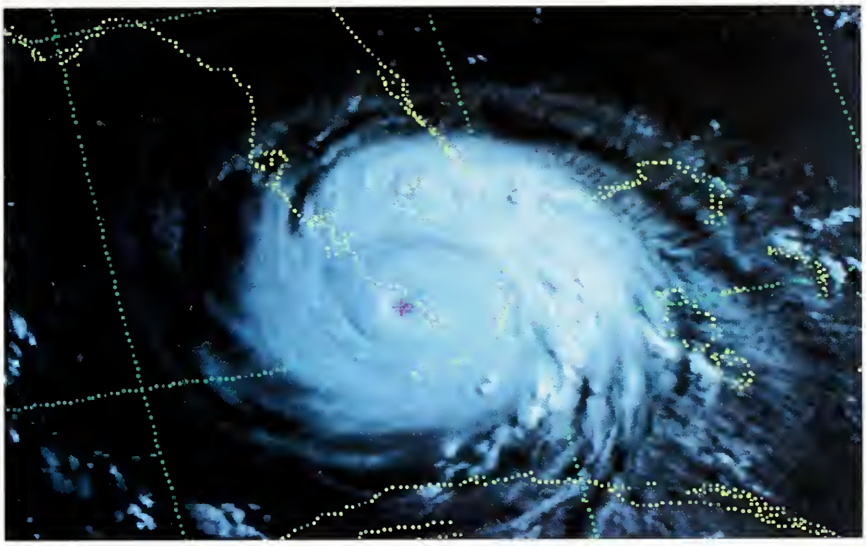
A few countries are taking steps to minimize use conflicts. For example, France, Italy, and Spain are inventorying existing and potential resources. Of Spain's 8,000-kilometer coastal zone, 42 percent is as yet unoccupied, and new laws and policies have been formulated to minimize unregulated development. The new policies define the coastal strip as public domain with limited access. Similarly, Israel's 190-kilometer coastal region is to a large extent unoccupied, or used for activities that do not require a coastal-zone location. Environmental agencies in many nations are responding to the increasing demand for expanded recreational activities by preparing regulations for resource protection. These are hopeful steps toward reducing conflict in the world's coastal zone.

This presentation is digested from the volume Coastal Zone Space: Prelude to Conflict *by Edward D. Goldberg, to be published by the UNESCO Press in 1993.*

Edward D. Goldberg has been a geochemist at the Scripps Institution of Oceanography for the past 44 years. His present research involves the nature of seawater's colloidal state and platinum group elements in the marine environment. Both his science and his nature are benign.

Heavy Weather in Florida

180 Hurricanes and Tropical Storms in 122 Years



Hank Brandli & Rob Downey

On August 24, 1992, this satellite photo of Hurricane Andrew was captured on a home-computer screen. Andrew is the costliest natural disaster in US history.

John M. Williams, Fred Doehring, and Iver W. Duedall

Today, with weather satellites operating around the clock, it seems impossible for a storm system to form and develop without our knowing about it. This knowledge is relatively new, however. Until shipping lanes were established, tropical cyclones developed and died completely undetected in the oceans. And for storms that occurred up through the Civil War, almost all the data we have are in the form of eyewitness reports.

For many years, the only reports on tropical cyclones were those relayed by ships passing through or near the disturbance. Radio operators aboard the ships would convey barometric pressure, wind speed, wave height, and storm movement information to land stations. After the development of radar (which the weather bureau began using during World War II) and other sophisticated devices and the advent of air reconnaissance, data on tropical cyclones became far more accurate and extremely valuable.

Beginning in 1953, storms have been given names for convenience of communication. This way, storm information and documentation is shorter, less confusing, and easier to remember. At first, only female names were used, but since 1979, storms have been identified with both male and female names: The first storm of the year is christened either male or female, and they alternate throughout the year. The US Weather Bureau, in cooperation with other countries, makes up a periodic list of names. The names of severe hurricanes (such as Andrew) are retired after being used once.

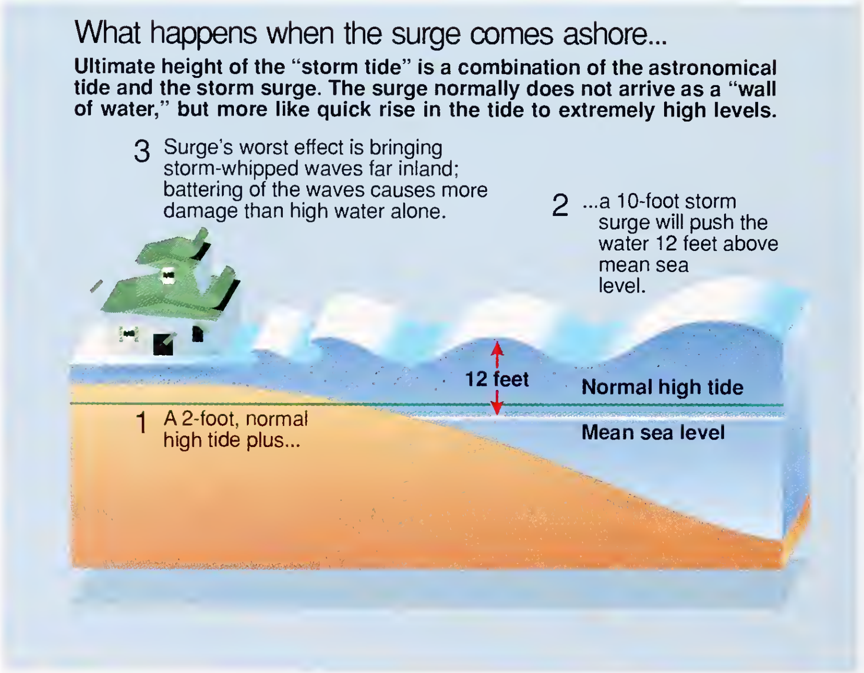
During the past 122 years, from 1871 through 1992, nearly 1,000 cyclones of either hurricane or tropical storm intensity have occurred in the tropical north Atlantic Ocean. About 180 of these have struck or passed immediately offshore or adjacent to the Florida coastline.

There appears to be a temporal pattern or cycle to tropical cyclones. In the first ten years (1870 to 1880), only four struck eastern Florida from the east or southeast, while 17 hit the western Florida coast and the panhandle. This pattern seemed to continue through the turn of the century.

From 1901 to 1930 there were fewer tropical cyclones (22 hurricanes and 17 tropical storms) than during the previous 30-year period, and the pattern shifted to more strikes from the southeast. With the exception of several hurricanes that zeroed in on the western Florida panhandle, most of the activity came from the Atlantic Ocean. Probably the worst was the September 1906 hurricane that all but destroyed Pensacola. Another hurricane struck Pensacola in July 1916, and in October of that same year still another storm brought 120-mile-per-hour winds to the same area. In September 1917, Pensacola got hit one more time.

In October 1910, a "Great" hurricane affected Key West, where it produced 15-foot storm tides and then moved through Fort Meyers and the middle of the state. In September 1919, Key West experienced an

This diagram shows in detail the effect of a surge on oceanfront property.



Air Reconnaissance

Aerial reconnaissance is vitally important to hurricane forecasters. Aircraft reports help meteorologists determine what is going on inside the storm as it actually happens. This, along with the broader view provided by data from satellites, floating buoys, and land and ship reports, makes up the total package of information available to the forecasters who must then determine the actual forecast of speed, intensity, and direction of the storm. In specially modified aircraft, well-trained crews penetrate to the core of the storm and provide detailed measurements of its strength as well as an accurate location of its center, information that is not available from any other source. This data is then relayed to the National Hurricane Center at Coral Gables, Florida. The US Air Force uses the Lockheed WC-130 *Hercules*, and NOAA uses the Lockheed P-3 *Orion*. Reconnaissance aircraft carry the most advanced weather observation equipment and computers, and have room for about 20 scientists. Since reconnaissance began in the Atlantic, Caribbean, and Gulf of Mexico in 1944, only one aircraft and crew has been lost—in 1955, to Hurricane Janet in the Caribbean.

even more violent storm that was later recognized as the first-known category-4 hurricane to strike the US.

But after 1919, the cycle of tropical cyclone activity took a different pattern. In September 1926, the first direct hit (that is, the storm hit almost perpendicular to the coastline) occurred at Miami. With the exception of the now well-known 1992 Hurricane Andrew, the 1926 storm was the worst to hit Miami. Then, in September 1928, the so-called "Great Lake Okeechobee Hurricane" struck the Palm Beach area. This category-4 storm tracked across the big lake's northern shore, causing the shallow waters to reach heights of more than 15 feet. This surge was forced southward, causing terrible flooding in the lowlands at the lake's south end. (A hurricane surge is an abnormal rise in water level that results from intense winds and low barometric pressure.) Thousands of migrant farmers died as water rushed over the area. After the storm, the Red Cross counted 1,836 dead, but still more bodies and skeletons were discovered in later years. The barometric pressure was measured at 27.43 inches. To prevent future similar disasters, dikes were built around the lake by the US Army Corps of Engineers.

From 1931 to 1960 there were 21 hurricanes in the tropical North Atlantic. Of these, 12 occurred during the 10-year period of 1941 to 1950. At an estimated $3 billion in damages (in 1990 dollars), this decade was the most costly until Hurricane Andrew caused an estimated $15 to $30 billion in damages. There were Florida hurricanes in 1944, 1945, 1947, 1948, 1949, and two in 1950; all of them were category-3 or -4 storms. Hurricane Easy, in September 1950, destroyed the fishing fleet and severely damaged or destroyed 50 percent of the houses in Cedar Key, on Florida's west coast. The tide was 7 feet in Tampa Bay. Easy did two loops just off the coast, which brought erroneous accusations from local residents that the weather bureau was seeding the storm (hurricane tracks usually are not loops).

Hurricane King, October 1950, was a small, violent, category-3 storm that raked the southeast Florida coast from Miami up through Fort Lauderdale, the Palm Beaches, and the Carolinas. The lowest barometric pressure recorded was 28.20 inches, and wind gusts hit 140 miles per hour.

Ranges for the Saffir/Simpson Scale

Scale Number (Category)	Central Barometric Pressure (inches)	Winds (mph)	OR	Surge (feet)	OR	Damage
1	28.94 or higher	74 to 95		4 to 5		Minimal
2	28.50 to 28.91	96 to 110		6 to 8		Moderate
3	27.91 to 28.47	111 to 130		9 to 12		Extensive
4	27.17 to 27.88	131 to 155		13 to 18		Extreme
5	Less than 27.17	Higher than 155		Higher than 18		Catastrophic

Jayne Doucette/WHOI Graphics

Predictions of hurricane severity and damage are frequently expressed in terms of the Saffir/Simpson scale. The National Weather Service assigns a category number to a storm when it becomes a hurricane. Category assignments are then continuously reevaluated as conditions change, and public-safety officials are kept informed. Because category assignments are based on observed conditions at a specific time in a hurricane's life, they are not considered forecasts, but rather are estimates of the amount of damage a hurricane would cause if it were to make landfall without changing its size or strength. Using this scale, a hurricane's disaster potential can be monitored, and appropriate precautions (such as regional evacuations) can be more effectively planned and implemented. The Saffir/Simpson scale was developed by Herbert Saffir, a consulting engineer in Dade County, Florida, and Robert H. Simpson, former Director of the National Hurricane Center.

Following an otherwise quiet period from 1951 to 1960, Hurricane Donna hit in September 1960. In 1990 dollars, Donna chalked up $1.8 billion in damage—the record to that date for a single storm!

Until Andrew, the hurricane most talked about was The Great Labor Day Hurricane that struck the Florida Keys on September 2, 1935. To this day, it is the most violent to strike a US coastline. As the hurricane surge reached nearly 30 feet, 408 people died. A railroad train was washed or blown off its track near Islamorada. Barometric pressure was 26.35 inches, then the lowest ever recorded in this hemisphere. (In 1988, Hurricane Gilbert brought an all-time low barometric pressure of 26.22 inches to the Caribbean. Although in the same hemisphere, Gilbert did not affect Florida.) By engineers' estimates, the structural damage indicated that wind speeds were 200 to 250 miles per hour. (As a recent comparison, Hurricane Andrew's highest clocked wind speed was 164 miles per hour.) The Flagler Railroad, the only land link to Key West, was destroyed, and US Highway 1 was later built on the roadbed. Although the Saffir-Simpson Scale was not in use until 1974, The Great Labor Day Hurricane was later classified as the first category-5 hurricane recorded in this hemisphere.

The final period, 1961 to 1992, included 39 storm systems. From 1961 through 1970, seven hurricanes hit Florida. For three years following, all was quiet and no hurricanes landed near. In 1964, three hurricanes

struck the Florida coast. In August 1964, Hurricane Cleo drew first blood, and was the first storm to strike the southeast coast since Hurricane King in 1950. With gusts over 135 miles per hour and a barometric pressure of 28.55 inches, Cleo was credited with 217 deaths and $600 million in damage that ranged from Miami through Ft. Lauderdale and as far north as the Carolinas. Cleo was called a "textbook" storm of Cape Verde vintage: Located some 300 to 400 miles off Africa's western coast (near 16°N latitude), the Cape Verde Islands are the spawning grounds of some of our most famous—and most powerful—hurricanes.

Next on the 1964 program was Hurricane Dora in September. She slammed into the St. Augustine area, almost penetrating to the Gulf Coast before executing a northward turn. After a run through Georgia and the Carolinas she headed out to sea, leaving over $1 billion dollars worth of destruction, much of it due to flooding and coastal damage from her 10- to 12-foot storm surge.

Then in October 1964, Hurricane Isbell came along. Spawned in the northwest Caribbean, she was a category-1 hurricane that moved northeast over western Cuba into Florida's southwest coast. She finally went out to sea near Palm Beach.

In 1965, Hurricane Betsy traversed a piece of Florida and the north Gulf Coast, bringing 75 deaths and costing $6.4 billion. Her erratic track kept everybody guessing. She zigzagged north of Puerto Rico to a point about 300 miles off Cape Kennedy (now Cape Canaveral) and stalled almost two days. Then suddenly she moved southwest into the Bahamas, where she stalled again. For 20 hours the islands were buffeted by 120- to 140-mile-per-hour winds. A dead-west track followed, taking her across the upper keys and southeast Florida into Florida Bay. From there the course was northwest into the New Orleans area. Top winds were over 160 miles per hour at Grassy Key before the anemometer was blown away.

In 1966 a hurricane named Inez sideswiped southeast Florida and the upper keys. After making an erratic run through the Caribbean,

Hurricane Betsy was a category-3 storm that hit Miami, Florida, in 1965. Winds reached 180 miles per hour, and the barometer dropped to 27.99 inches. This is the northern portion of the storm as it passed south of Miami.

Miami Herald

Cuba, and the Bahamas, Inez finally died in the mountains near Tampico, Mexico. Both Betsy and Inez were classified as strong category-3 hurricanes, but the air-reconnaissance team in Inez clocked wind gusts to 190 miles per hour near Haiti.

Agnes, in 1972, and Eloise, in 1975, are worthy of mention. While barely a category-1 for less than a day, Agnes nevertheless killed 122 people and chalked up over $6 billion in damages. She struck the Florida panhandle, then merged with another system in the mid US. Hurricane Agnes triggered torrential rains and extreme flooding that caused destruction throughout the entire eastern seaboard. Eloise also hit the panhandle as a category-3 storm, causing 80 deaths and over $1 billion in damages.

With over 50 lives lost and estimates of $15 to $30 billion in property damage, Hurricane Andrew is the worst natural disaster to befall the US.

In 1985, Hurricanes Elena, Kate, and Juan all affected Florida. Elena never made a landfall on the Florida shores but stayed just far enough offshore to cause over $1 billion in flood damage. A mass evacuation of over a million people didn't help matters—being the day before Labor Day, confusion reigned as vacationers had their holidays spoiled while Elena stalled off Cedar Key. A category-3 storm, Elena affected Florida from Venice to Pensacola.

Hurricane Kate in November 1985 started north of Puerto Rico and moved through the southeast Bahamas and northern Cuba. She curved north into the Gulf to strike the panhandle as a category-2 storm, then moved through the eastern US. She caused "Hurricane Warnings" to be posted along Florida's southeast coast for the first time since Inez back in 1966. (A Hurricane Watch is issued for coastal areas when the threat of storm is within 24 to 36 hours; a Hurricane Warning is posted when the threat is 24 hours or less.) Although Hurricane Juan did not strike the coastline, it nevertheless affected the extreme northwestern Florida panhandle from October 25 to November 1, 1985. That Halloween, Pinellas, Manatee, Sarasota, and Lee counties were pounded all night by the storm's spiral bands.

While 1990 produced 14 named storms (the most since naming began in 1953), 1991 only had half that many. Tropical storm Marco affected the northwest portion of Florida slightly, and the disturbance named Klaus came to the central and north-central regions of Florida in 1990. Only the extreme southeast tip of Florida had a brush with tropical storm Fabian during 1991. Hurricane Bob, potentially the most serious storm of the 1991 season, headed toward the Miami-Palm Beach area in August. But 200 to 300 miles off the Florida coast it executed an almost-90° turn to the north, and missed the entire state. So, the Sunshine State escaped once again (much to the chagrin of the northeastern US, which was hit).

The 1992 season began with several tropical depressions, but otherwise June, July, and most of August were deadly quiet. The last time hurricane season started late was in 1977, when Hurricane Anita started in the Gulf of Mexico on August 28. But on August 14, 1992, satellite photos indicated a strong tropical wave off the African coast near the Cape Verde Islands. This system moved west for two days and developed into a tropical depression near 11.6°N and 40.6°W on August 17. By noon on the 17th the winds were 40 miles per hour and tropical storm Andrew was named. This position was about 1,175 miles east of the Lesser Antilles.

By August 20 Andrew's tropical storm status was in trouble! Winds were up to 45 miles per hour, but barometric pressure was that of normal sea level, and the whole system was shaky. At this point, San Juan,

Puerto Rico, was only 350 miles southwest, but Andrew had slowed down. The next morning, however, winds increased to 60 miles per hour and pressure dropped to 29.71 inches. By 11 p.m. on August 21, Andrew was 610 miles east of Nassau, in the Bahamas, with 65-mile-per-hour winds.

Chuck Fadely/Miami Herald

Aftershock: The force of Hurricane Andrew blew the walls off the Saga Bay apartment building, yet left the furnishings behind.

The morning of August 22, air reconnaissance confirmed that "Andrew is now a hurricane." Winds were 75 miles per hour, barometric pressure was 29.35 inches, and the storm was 800 miles east of Miami, Florida. Later that same day Andrew became a category-2 hurricane, and the next morning air reconnaissance announced that the storm had been upgraded to category 3. Winds then were 120 miles per hour and pressure was 28.08 inches.

By noon of August 23 Andrew was a category-4 storm. Pressure had dropped to 27.46 inches. It was 330 miles east of Miami, moving dead west at 16 miles per hour. That afternoon Andrew peaked with top winds of 150 miles per hour and barometric pressure of 27.33 inches. A hurricane "watch" was posted from Titusville, Florida, south to Vero Beach, and a "warning" was posted south through the keys and up to Fort Meyers.

Between 5:00 and 6:00 a.m. on August 24, Andrew struck Florida's east coast just south of Miami, as a category-4 storm. At the National Hurricane Center in Coral Gables, winds were clocked at 164 miles per hour at peak, and the coastal storm surge soared to 16.9 feet.

Andrew crossed Florida at 16 to 18 miles per hour and emerged into the Gulf of Mexico finally to strike the Louisiana coast between Lafayette and New Iberia on August 26. In the southeast US Andrew took a north-northeast turn, and finally died in Pennsylvania on August 28 after waning to a rainstorm.

With over 50 lives lost and estimates of $15 to $30 billion in property damage, Hurricane Andrew is the worst natural disaster to befall the US. Untold serious damage was inflicted on the natural marine environment, including the coral reefs and seabed.

While Florida is often considered synonymous with sunshine, it also brings to mind summer or fall tropical storms and hurricanes. Indeed, one historical account of hurricanes shows that between the years 1493 and 1870, the Caribbean area and Florida experienced nearly 400 hurricanes. Florida will continue to be hit by hurricanes. And the recent disaster caused by Andrew has greatly strengthened the public's view on the ferocity of such storms. NOAA, through the National Hurricane Center, performs a great service in keeping the public updated on the status of hurricanes. While hurricane tracks cannot be predicted, past hurricane performances provide a good educated guess on when and where a storm will go. Andrew will not be the last hurricane to strike

Florida, though it did provide a bitter lesson on the extreme vulnerability of coastal states like Florida. There is no practical criteria to avoid damage caused by a major hurricane. The best one can do is to be aware of the fact that hurricanes are deadly and can cause catastrophic destruction and that hurricane preparedness is an essential, never-ending process. ✪

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This article is condensed from 122 Years of Florida Hurricanes and Tropical Storms, *a report by the authors. It will be available in June 1993 from Florida Sea Grant College, Gainesville, Florida.*

Our friend and colleague, Fred Doehring, pictured at right, died on January 5, 1993, a few weeks after this article was submitted to Oceanus. *Until his death, Fred had spent the last 18 months painstakingly researching data for* 122 Years of Florida Hurricanes and Tropical Storms *by Fred and us. Fred had a genuine interest in Florida Tech, and in helping students find information on weather. We thoroughly enjoyed working with Fred and we are hopeful that Fred's book and this condensed version of it will enhance hurricane awareness.*

—John Williams and Iver Duedall

Tides and Their Effects

Chris Garrett and Leo R.M. Maas

The great Master of Philosophy drowned himself, because he could not apprehend the Cause of Tydes; but his Example cannot be so prevalent with all, as to put a Period to other Mens Inquiries into this subject.

—Richard Bolland, 1675

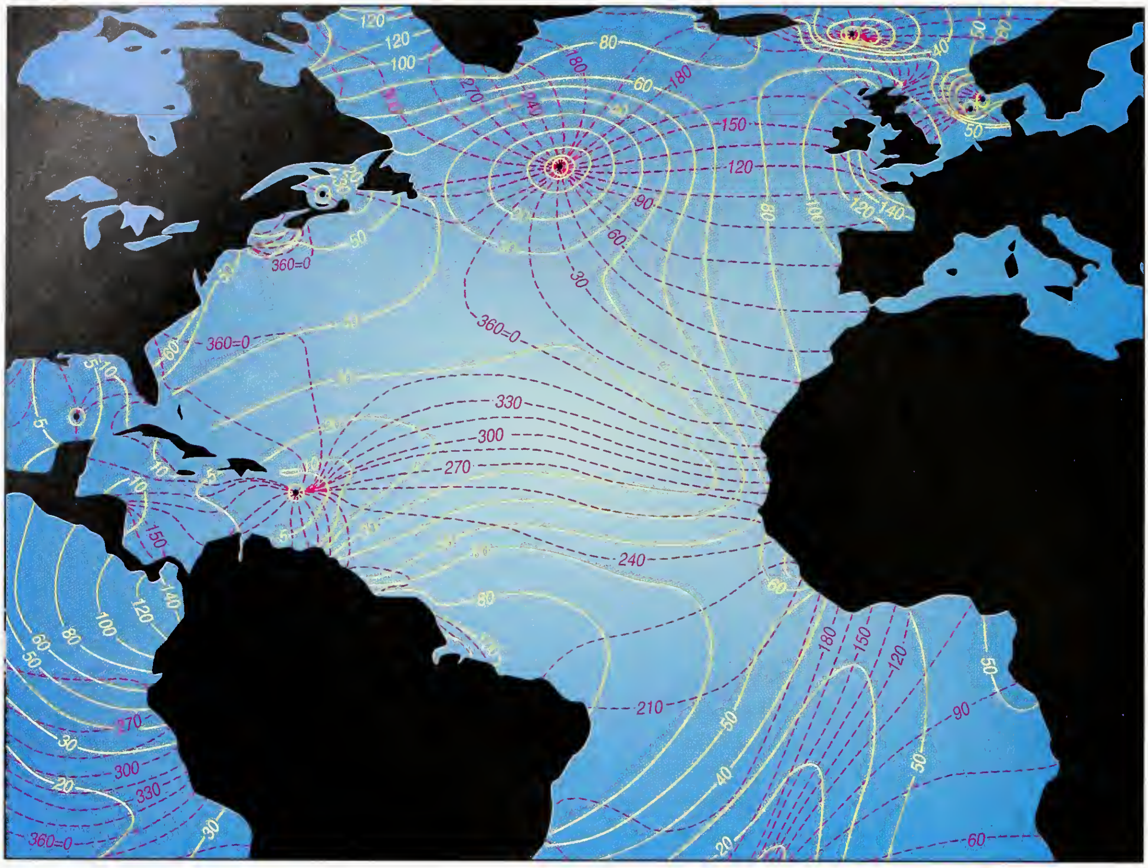
We may be surprised by this mythical account of Aristotle's reaction to the complicated currents of the Euripus in Greece, and assume that "other Mens Inquiries" have long since solved all the problems of tides in the world's oceans. But much of our understanding of the effects of tides in the coastal ocean is recent, and some important puzzles remain. Interest in tidal problems ebbs and flows like the tides themselves, but it is now fully recognized that tides do more than alter the water level in harbors; they affect many facets of circulation and mixing in continental shelf seas.

Tides affect many facets of circulation and mixing in continental shelf seas.

Tidal Theory is Based on Newton's Theory of Gravitation

Isaac Newton's 1687 theory of gravitation provides the basis for tidal theory: The earth and moon rotate around each other, with centrifugal force and gravitational attraction balancing one another. However, the gravitational force, which decreases with increasing distance, is greater than average on the side of the earth facing the moon, and less than average on the opposite side. If the earth were entirely covered by water, the ocean would bulge up both beneath the moon and at the antipodean point on the opposite side of the planet. As the earth rotates, any given location experiences both of these bulges, leading to two high tides a day. Unless the moon is over the equator, these tides are generally of different heights. As the moon makes its approximately 27.3-day revolution around the earth, it moves about 13° each day. The earth's daily rotation in the same direction requires an extra 50 minutes to match the moon's 13° movement, so high tides generally occur every 12 hours and 25 minutes.

The sun also exerts tide-producing forces at the earth's surface. Newton's law maintains that gravitational force is directly proportional to the mass of the bodies—the larger the body, the greater the force—and inversely proportional to the square of the distance between them—the



Jayne Doucette/WHOI Graphics

The Atlantic 12.4-hour tide, as predicted by E.W. Schwiderski's numerical model, resembles waves rotating counterclockwise (with the dashed lines joining places where high tide occurs at the same time—the numbers are the phase lag, 30 degrees represents a delay of about 1 hour). The amplitude (solid lines, in centimeters) increases outwards from amphidromic points where there is no tide.

greater the distance, the smaller the force. This explains why the sun's gravitational pull on the earth is only about 46 percent that of the moon: though larger than the moon, the sun is much farther away. The main solar tide has a period, or repeat time, of 12 hours.

The actual tidal forcing is made up of these two main "constituents," plus many others that are associated with details of the orbits of the earth, moon, and sun. For example, there is an important constituent with a period of 12.7 hours associated with the elliptical orbit of the moon. This forcing, which is 19 percent of that of the 12.4-hour forcing, adds to it at perigee (when the moon is closest to the earth) and accounts for the big tidal forces then. Two weeks later, however, the two forces oppose each other to account for the weaker forcing at apogee (when the moon is farthest away from earth).

Continents greatly complicate the tides, but we can predict tidal rise and fall at any one place using past tidal records because the periods of the forcing constituents are not affected. Coastal tides have been measured since 1831 by the rise and fall of a float inside a "stilling well" connected to the outside water by an orifice small enough to suppress wind-generated waves. Once the constituents have been separated by mathematical analysis of the record, they can each be projected into the future and recombined to make a prediction of future water levels.

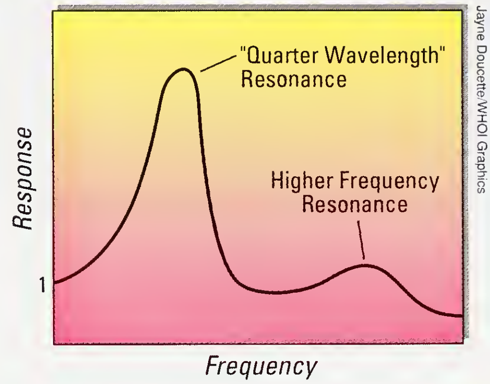
Resonance

The concept of resonance can be illustrated by analogy with an AM radio. The signal from the broadcasting station has a particular frequency, and the internal circuitry of the radio has a natural frequency that can be adjusted by turning a knob. Beginning at the low end, as this internal frequency approaches the transmitter frequency, one begins to receive a signal, with maximum response (resonance) when the two frequencies match, and a diminishing response again as the radio is tuned to a higher frequency. Note that while the amplitude of the response varies, its frequency is always that of the transmitter, or forcing function. The radio is designed to have a very narrow resonance peak to avoid interference.

The ocean basins may also have various natural oscillations that are close to resonance with the direct tidal forcing, but with broad resonance peaks because of friction. The response depends on the difference between the natural and forcing frequencies, on friction, and also on how well the shapes of the forcing and the natural oscillations match.

For a bay excited by tidal forcing from the open ocean, the response is unity at very low frequency, for which the water has time to reach the same level everywhere, and very small at high frequencies, at which the bay does not have time to respond. Resonance may occur at several frequencies in between; the most important, known as the "quarter-wavelength resonance," occurs when the tide advancing into the bay is reflected and returns to the entrance just in time to receive another push from the next oncoming tide.

The resonance peak is high and sharp if the bay is well separated from the ocean by a narrow entrance or major depth change and has little seafloor friction; the peak is lower and broader if the separation is less marked, or if there is significant friction.



High water for each constituent tends to circulate around "amphidromic points" where there is no tide, and bulge around ocean basins. Larger tides occur near the coasts. The tide may be further amplified on continental shelves by shallow-water effects that can include a near-resonant response in some regions. The world's highest tides, for example, occur near the head of the narrow, funnel-shaped Bay of Fundy, where the vertical range from low to high water can reach 16 meters. This is largely a consequence of a near-resonant response (see Box) of the Bay of Fundy and Gulf of Maine, which is a separate system from the North Atlantic because of the 20-fold change in depth from shelf to deep ocean. It has a natural period of about 13.3 hours, close enough to the 12.4-hour tidal period to respond vigorously to the Atlantic forcing.

The other important lunar constituent, with a period of 12.7 hours, is even closer to resonance and overtakes the 12-hour solar tide in importance. A consequence of this is that the tides in the region vary more over the one-month apogee-perigee cycle than over the two-week spring-neap cycle.

Spring-Neap Variations, the Age of the Tide, and Nodal Modulation

Variation in the tides from springs to neaps is well known; a conventional explanation is that large, spring, tides occur at full or new moon, when the moon and sun are aligned and pulling together, and small neap tides occur at the moon's quarters, when the moon and sun pull at right angles. However, a cursory examination of tide tables in most places with semidiurnal (twice-a-day) tides shows that the highest tides in a month tend to occur a day or two *after* the full or new moon! This lag, known as the "age" of the tide, was first recorded in 77 A.D. by Pliny the Elder, who attributed it to "the effect of what is going on in the heavens being felt after a short interval, as we observe with respect to lightning, thunder, and thunderbolts." Unfortunately this delightful theory has been discredited by recognition that light and gravity travel at the same speed. Modern theories relate the age of the tide to the near-resonant response of ocean basins themselves, but with the response limited by seafloor friction and the spatial mismatch of the response and the tidal forcing.

Canadian scientists had some fun with proposals to tune the Bay of Fundy to resonance.

Tidal forcing and response are also modulated on longer time scales. One intriguing variation, known as the "nodal modulation," occurs over a period of 18.6 years and is associated with the moon's varying declination (movement of the moon's orbit toward the Equator). The total tidal forcing does not change, but its split into semidiurnal and diurnal (once a day) forcing does. This means that in most locations where the semidiurnal response dominates, the tide follows the modulation of the 12.4-hour forcing, and the next maximum will be in 1997. The effect is small (only about 3.7 percent), and tide predictions based on just a few years of data usually assume that the semidiurnal response will be modulated by the same amount. However, an analysis of some 50 years of sea-level data from Saint John on the Bay of Fundy, and 20 years from Bar Harbor and Boston on the Gulf of Maine, reveals an actual modulation of about 2.4 percent. This subtlety actually helped to support the theory and modeling that attributed the high tides of this region to a near-resonant response, but with allowance for bottom friction, which depends on the square of the current and so helps to reduce the effect of increased forcing.

Tidal Power is Expensive to Harness

The success of the theory in accounting for natural changes in tides increased confidence in predicting changes that would accompany Canadian development of tidal power in the Bay of Fundy's upper reaches. The simple expectation that barriers would effectively shorten the bay and bring it closer to resonance, with a consequent increase in the regional tides, was borne out in detailed modeling by David Greenberg (Bedford Institute of Oceanography). The predicted increase for the largest scheme discussed (with a proposed capacity of about 5,000 megawatts) was about 10 percent at Boston. Although a small change on its own, this is enough to slightly increase the possibility of flooding from tide and storm surge together. (Canadian scientists had some fun with proposals to tune the Bay of Fundy to resonance, generate tidal power, and then sell it south of the border to Bostonians wanting to

pump out their flooded basements! They claimed that it represented a new export market and revenge for acid rain all in one.)

A 240-megawatt tidal power plant built nearly 30 years ago at La Rance in Brittany, France (see the photo on page 14), is still in operation, and a 20-megawatt pilot plant was built at Annapolis Royal in Nova Scotia in 1983, but plans for the big Fundy schemes, and others around the world, have receded for the present, mainly because construction costs for these facilities are so high that it would take many years to reap a return on the investment.

Michael Woodward

C. Garrett

A 7-meter-per-second tidal current rushes in Nakwakto Rapids, British Columbia, Canada (left), and a tidal bore advances up the Qian Tang River in China (right).

Topography, Water Depth, and Other Factors Influence Tidal Currents

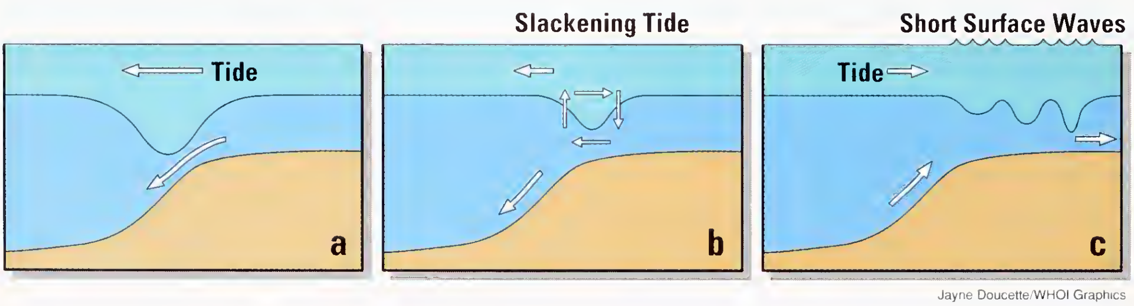
While tides are vertical changes in water level, tidal currents are horizontal water movements that are caused by the varying tides. At a particular location, tidal currents may be predicted from past records in the same way as tides themselves are. Relying on this to prepare current atlases is unsatisfactory, however, because tidal currents vary over short distances due to changes in topography. With increasing computer power, there has been a tendency in many parts of the world toward developing numerical models based on the laws of physics. These express little more than the tendency for water to flow downhill, while being pulled to the right (in the Northern Hemisphere) by the Coriolis force and slowed by bottom friction. Many models deal only with the depth-averaged current, but theories and observations both demonstrate that the current decreases toward the seafloor, with an interesting feature: If the current at each depth is split mathematically into one part that rotates clockwise in time and another that rotates counterclockwise, the latter increases more rapidly away from the bottom and tends to dominate near the seabed.

Tidal constituents (or frequencies) other than those present in the tidal forcing result from the nonlinear nature of friction that tidal currents experience at the seafloor, and from the advective nature of tidal currents. Tidal currents not only advect (transport) plankton, pollutants, and other floatables, but, if for some reason (usually related to variable

water depth) the tidal currents show a variation in strength or direction, this variation itself is advected by the tidal current. This is the prime nonlinear effect of fluid flow. The appearance of "higher harmonics" (whose frequencies are a multiple of that of the basic, say, semidiurnal tide, or whose periods are a fraction of that of the tide) is the first indication of the importance of this advective nonlinearity. Its effect is most pronounced in shallow water, where an advancing high tide tends to steepen, leading to the production in some rivers of a tidal bore, a wall of water much like surf approaching a beach.This same tendency is present, though at a much larger scale, in the interior of a stratified ocean when the depth-averaged current flows over abrupt topography.

If we assume the ocean consists of two layers (a shallow, warm, fresh layer atop a deep, cold, salty layer), a tidal current flowing off-slope produces a depression in the interface. This depression, like an inverted bulge of water, tries to flatten itself by propagating both on- and off-shelf. However, when the basic tidal current is strong enough, the bulge is unable to propagate against it and is arrested above the sloping region. Once the tide slackens, this shelfward-propagating wave is no longer checked, but moves onto the shelf and evolves into an "internal bore." The internal bore usually breaks down into a number of solitary waves in which the nonlinear tendency to steepen is exactly balanced by the tendency to disperse. This breakup of the tidal bore into successively smaller solitary waves is intimately related to the fact that the speed of

Schematic of internal tide generation (a), its subsequent propagation onto the shelf (b), and its eventual breakup into a number of solitary waves (c). Thin arrows indicate water motion, thick arrows the progressing wave. Changes in surface wave pattern occur at locations that depend on factors such as the wind direction.



these waves is proportional to their amplitude. The surface currents associated with these internal solitary waves modify any short wind waves present, and render them visible, even from space. Their eventual decay helps to provide energy for the upward mixing of nutrients that marine life depends upon. In this way the combination of tide and topographic slope exercises a curious form of remote control on biological production.

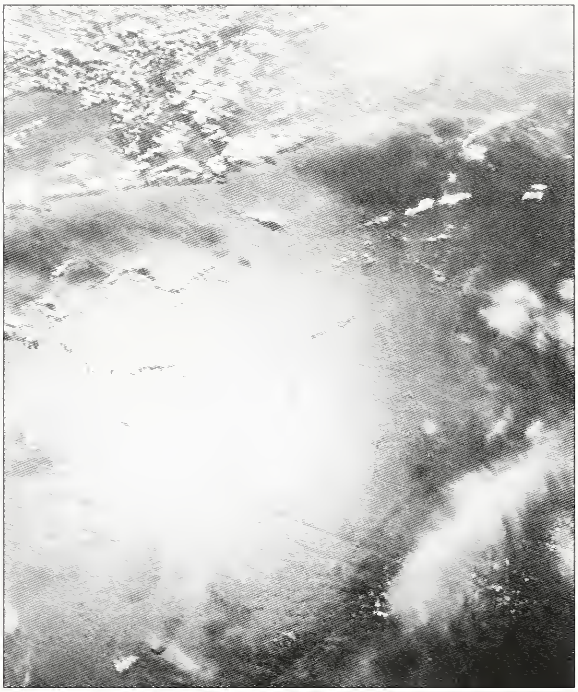
Mean Current Generation and the Dispersion of Matter

The advection of spatial variations in the tidal current by the tidal current itself not only generates higher harmonics (and solitary waves) but also produces a mean current. Unlike oscillatory tidal currents, a mean current can cause the net displacement of a fluid parcel over a tidal period. This is exemplified by a tidal flow's acceleration on passing a headland; the tidal flow enters the headland region smoothly, but continues as a jet, leaving an eddy in the lee of the headland. The opposite flow structure appears in the reverse tidal phase, so that residual

vortices will on average be found on both sides of the headland. An example of this, recently studied by Richard Signell (US Geological Survey) and Rocky Geyer (Woods Hole Oceanographic Institution) occurs at Gay Head on Martha's Vineyard. The mean flow in this case is usually localized, being restricted to the coastline's irregularities, hence there is no large-scale transport of the water and anything in it.

However, work initiated by John Huthnance (for his Ph.D. at Cambridge University) in the UK and applied to Georges Bank by Canadian oceanographer John Loder (for his Ph.D. at Dalhousie University) shows that extensive mean currents are produced by tidal flow over submarine banks and the steep slope of the continental shelf edge. The physical mechanisms and associated mathematical theories are quite complex (see the Box on page 33), but produce a mean current that in the Northern Hemisphere has the shallow water to the right facing downstream. This mean current at a fixed position, as would be measured by a moored current meter, is called the Eulerian mean current (for the 18th-century Swiss physicist Leonhard Euler). A fluid particle may experience an additional "Stokes drift" (named for the 19th-century English physicist Sir George Stokes) due to spatial variations in the magnitude of the oscillatory tidal current. For example, if the tidal motion is more or less circular, but increases in magnitude over shallower depths, a fluid parcel will be advected more strongly over the shallower regions and hence will acquire a net displacement. The total motion of a fluid particle is called the Lagrangian mean current (after the 18th-century French physicist Joseph Lagrange) and is related to the Eulerian mean current observed at a fixed position in space by a relationship that is popularly abbreviated as "Lagrange = Euler + Stokes." (This should not carry the implication that a Frenchman is a match for a Swiss citizen and an English gentleman combined!) On the sides of Georges Bank, the Stokes drift is in the opposite direction to the Eulerian mean current and only about one-third as big, so that the mean Lagrangian, or particle, motion is in the same direction as the Eulerian mean flow, clockwise around the Bank, but at about two-thirds the rate.

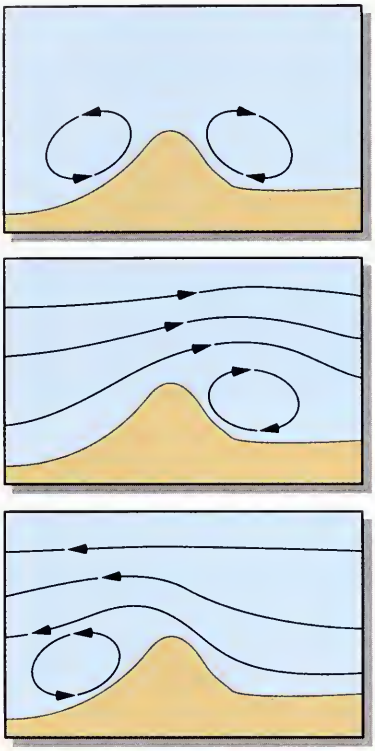
The mean current magnitude is dependent on the ratio of the width of the sloping region to the distance that a particle travels in half a tidal cycle (the tidal excursion, approximately 14 kilometers for a tide of 1 meter per second), and is strongest when these two length scales match. There appears to be a worldwide tendency for sandbanks generated in shallow seas to meet this requirement and also to be oriented with respect to the tidal current, such that the two residual current generating mechanisms (see the Box) are in tune. (In the Northern Hemisphere this requires a counterclockwise turning of these elongated underwater



Surface traces of a series of internal solitary waves in the Andaman Sea (depth about 1,400 meters), west of Thailand, as seen from the Apollo-Soyuz *spacecraft. North is to the left. The 100-kilometer-long solitary waves, which are visible at the sea surface due to the effect of the associated currents on short surface waves and hence on sun glitter patterns, propagate towards the west-coast of Thailand in the upper part of this photograph. They are about 15 kilometers apart and originate from the tides flowing over a sill located some 300 kilometers away. White regions are clouds.*

dunes with respect to the dominant tidal current direction.) This suggests the existence of some interesting but not yet fully resolved feedback mechanism between a sandy bottom and the tidal flow above it, each "shaping" the other.

Although one might anticipate that the existence of a mean flow over a feature like the continental shelf slope could contribute greatly to the dispersion of matter, this would normally not be expected to occur in regions where the mean-flow streamlines are closed. However, work largely pioneered by Jeff Zimmerman (Netherlands Institute for Sea Research) demonstrates that irregular particle paths may well result in this circumstance, even from regular velocity fields that lack any turbulent component. To appreciate this, consider a sequence of residual cells (generated by either of the processes discussed) in which particles, in the absence of a tidal current, would just circulate around their centers, following the streamline pattern. Then, when a periodic (tidal) current is superimposed on this, it might advect particles from one cell to the next. Depending on the relative strength of the tidal current to the residual current, particles may be advected back to the original cell during the reverse tidal phase, so that their mutual distances are not greatly affected. However, when some particles manage to stay in the neighboring cell (or even further away), their distance from some originally close-by particles is substantially increased, a process known as "chaotic stirring."



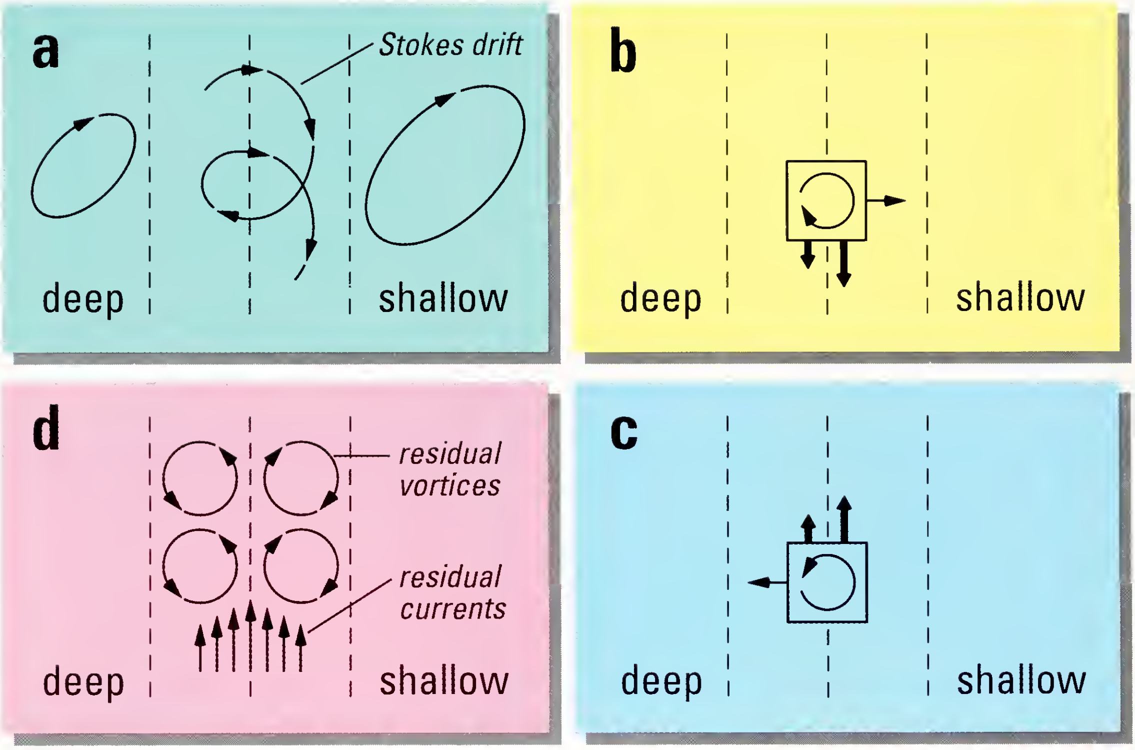
Jayne Doucette/WHOI Graphics

The net (mean) flow pattern of two phases of tidal flow past a headland. The water approaches the headland smoothly, but leaves it as a jet, creating a vortex in its lee.

Tidal Mixing

Turbulence generated at the seafloor by the tidal currents can exert important influences on the average density structure of the coastal ocean. In spring and summer this vertical mixing competes with the stratifying influence of surface heating. As recently as 1974, John Simpson and John Hunter (University College of North Wales) pointed out, on energetic grounds, that a very good indicator of the winner of this competition is the single parameter (which now bears their names) of water depth divided by the cube of the maximum tidal current. For large values of this parameter, the water can become stratified like a lake, whereas for small values it is kept well-mixed throughout the summer. For the shallow seas around England, for the Fundy/Maine system, and for many other shelf areas, the dividing value is about 70 seconds cubed per square meter, so that a 1-meter-per-second tidal current can keep 70 meters of water well mixed. The effect shows up in oceanographic data and also in sea-surface temperature measurements made from space (on clear days) by observing the infrared emissions of the sea surface; well-mixed areas such as the Bay of Fundy and Georges Bank are kept cold at the surface by the mixing, though the shallowest parts of the mixed regions, such as the center of Georges Bank, may still heat up more than their surroundings as there is less water to heat.

Tidal mixing in shallow seas is clearly of biological importance, because it promotes productivity by returning nutrients to surface waters—unless the water is so deep that phytoplankton receive insufficient



Jayne Doucette/WHOI Graphics

Tidal current ellipses and the resulting Stokes drift (a); residual current generation by tidal flow over a sloping bottom due to differential Coriolis forces (b, c) (two phases of the tidal flow); and (d) the net vorticity and mean flow pattern. Thin arrows indicate the water motion; thick arrows indicate the Coriolis forces acting on the sides of the fluid parcels. As the generation process is independent of the position along the slope, the residual current is parallel to it.

light as they, too, are mixed up and down. In this respect, frontal regions between tidally mixed and stratified regions are of particular interest: Nutrients mixed to the surface on the side of the front where the nutrient level is high but the average light available to vertically mixed phytoplankton is too low for growth may be stirred across the front into the stratified region, where nutrients have been depleted but phytoplankton can remain in the well-lit upper part of the water column.

Global Importance

Seafloor turbulence associated with tidal currents dissipates a considerable amount of energy. For the Fundy/Maine system calculations based on models and data show this to be about 50,000 megawatts. The value is less well-established for other shallow seas, though it is known to be large in the seas around Britain and off the Patagonian coast of Argentina. However, the total global dissipation rate has become increasingly well known in recent years through a variety of estimates. The most direct of these calculates the rate at which tidal forces work against the vertical velocity of the sea surface; this is known from satellite altimetric mapping of the sea surface as well as from numerical models of open-ocean tides. According to estimates by David Cartwright and Richard Ray (NASA Goddard Space Flight Center), the global energy dissipation is 2.55 million megawatts for the 12.4-hour lunar tide, and about 20 percent higher for all the lunar tides. Corresponding to this, the moon is moving away from the earth by about 37 millimeters each year, a rate that has been confirmed to within 5 percent by James Williams, Skip Newhall, and Jean Dickie (Jet Propulsion Laboratory) using measurements

Residual Currents

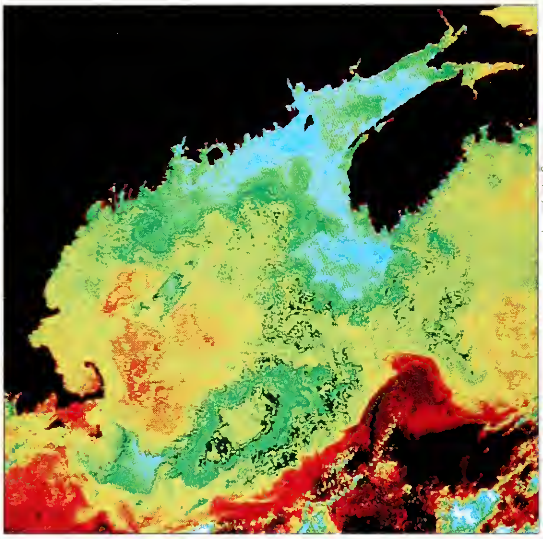
Eulerian "residual currents" (the currents which result after the purely oscillatory part has been mathematically removed) can be generated in the vicinity of a sloping bottom by differential Coriolis and differential bottom frictional forces. Both of these forces vary depending on the tidal-current speed that a fluid particle experiences at its sides when these sides are over different water depths. As an example, consider a fluid particle that is advected upslope by the tidal current. Its front side, being over shallower depth, is moving slightly faster (the shallower depth requires the flow to speed up, in order to be able to transport the same amount of water) and hence experiences a larger Coriolis force than the rear side. The net clockwise torque experienced by the particle translates into a net clockwise rotation (or "vorticity") that itself is advected upslope in this phase of the tidal flow. The reverse process—the generation of counterclockwise vorticity and downslope transport of it—appears in the off-shelf phase of the tidal current. Averaged over a tidal cycle, then, a pair of counter-rotating steady currents are generated. This happens at every point along a uniform along-shelf bottom profile, and leaves the residual, or mean Eulerian, current flowing parallel to the bottom contours with (in the Northern Hemisphere) the shallow side to the right when facing downstream. For a current rotating clockwise (as is usual for Northern Hemisphere currents) the Stokes drift will be in the opposite direction to this. Hence, in this case, the total particle drift velocity, the Lagrangian current, will be weaker than the local Eulerian current. The opposite will occur for a current rotating counterclockwise. The actual production of the Eulerian mean flow is subtly dependent on the presence of bottom friction, since in its absence the generation of, for example, clockwise vorticity and its subsequent advection, are exactly out of phase, and therefore would vanish when averaged over a tidal period. The presence of friction provides the necessary phase shift between the two above processes, leading to a nonzero residual current. Remarkably, the generated residual current is strongest when the frictional coefficient is weakest (but remains nonzero)! Apart from this catalyzing role, (differential) bottom friction acting on a tidal flow may also directly drive a mean flow all by itself; this may add to or subtract from the previously discussed mean flow, depending on the orientation of the tidal current with respect to the depth contours.

of the changes in travel time of a laser beam bounced off reflectors first placed on the moon by *Apollo* astronauts in 1969.

The solar tides add a further 20 percent or so to the tidal dissipation, which totals about 3.6 million megawatts altogether. This decreases the earth's rotational energy, giving a 1-second increase in the length of the day every 41,000 years. A major remaining oceanographic puzzle concerns whether the dissipation occurs mostly in shallow seas, or whether a significant fraction involves deep-ocean generation of tidal-frequency internal waves that travel into the stratified ocean interior and cause turbulent mixing.

While the phenomenon of tides has been known as long as the shores have been inhabited, its multifaceted effects only slowly unfold. This makes for a fascinating research topic, with ever further-reaching environmental applications. ✪

Chris Garrett spent his first undergraduate year in a room that had been Isaac Newton's attic, but chiefly remembers the lack of heating in England's coldest winter for 80 years. He stayed at Cambridge for his Ph.D., but then defected to the west, spending a year at the University of British Columbia and two years at Scripps Institution of Oceanography (University of California, San Diego) before moving to the Department of Oceanography at Dalhousie University in Halifax, Nova Scotia. His scientific interests have largely moved on from tides to questions of ocean mixing and air-sea interaction, and he occasionally enjoys working on more immediately practical topics involving unrelated things like icebergs and radioactive waste. After 20 years in Nova Scotia he recently returned to the Pacific southwest (Canada's), where he is at the School of Earth and Ocean Sciences and the Department of Physics and Astronomy at the University of Victoria, but he still welcomes invitations to visit Woods Hole....



Bedford Institute of Oceanography, Department of Fisheries and Oceans, Canada

A false color image of sea-surface temperature (blue is cold, red is warm) in the Bay of Fundy and Gulf of Maine on 27 August 1984. Tidal mixing keeps the surface cold in the Bay of Fundy, over Nantucket Shoals south of Cape Cod, and over Georges Bank (though the center of this, like the upper reaches of the Bay of Fundy, is shallow enough to have become warm by late summer even though well-mixed). The rest of the Gulf of Maine is stratified and warm at the surface; the red ribbon to the south is the Gulf Stream, with a few patches of

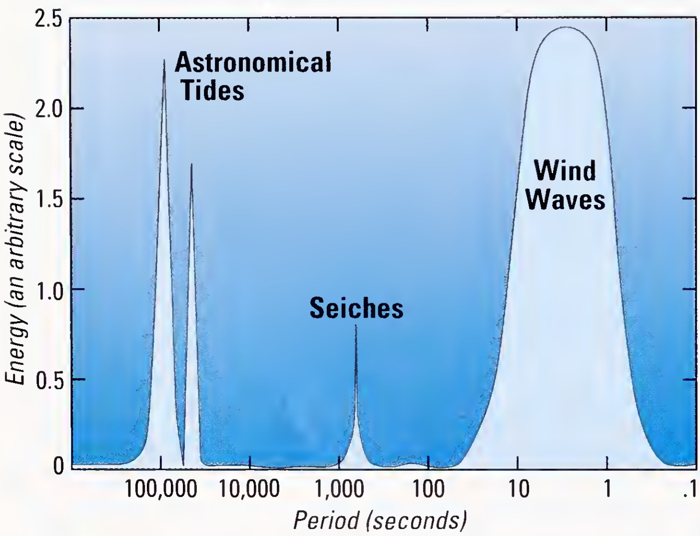
Being born in an area of the Netherlands that has been frequently flooded in the past may have subconsciously raised Leo R.M. Maas's interest in the untamed behavior of the ocean. Consciously, an interest in natural phenomena that occur on time and length scales "that we live in" led him to study physical oceanography at the University of Utrecht. After his Ph.D. he continued his research on tides at the Netherlands Institute for Sea Research, albeit, now being behind safe dikes, taking an occasional detour to study some more elementary fluid dynamical and mathematical topics. Having never visited Woods Hole, his desire to receive an invitation to do so is, possibly, even greater than that of his co-author....

Coastal Seiches

Graham S. Giese and David C. Chapman

Coastal residents associate the sea with particular rhythms: the short, insistent lapping of small harbor waves, or the long beat of ocean swell rolling toward shore from distant storms at sea. The rhythms might be the coming and going of the tides; for some coastal dwellers, these have a daily cadence; for others, the rhythm has two beats each day (see Tides and Their Effects, page 27).

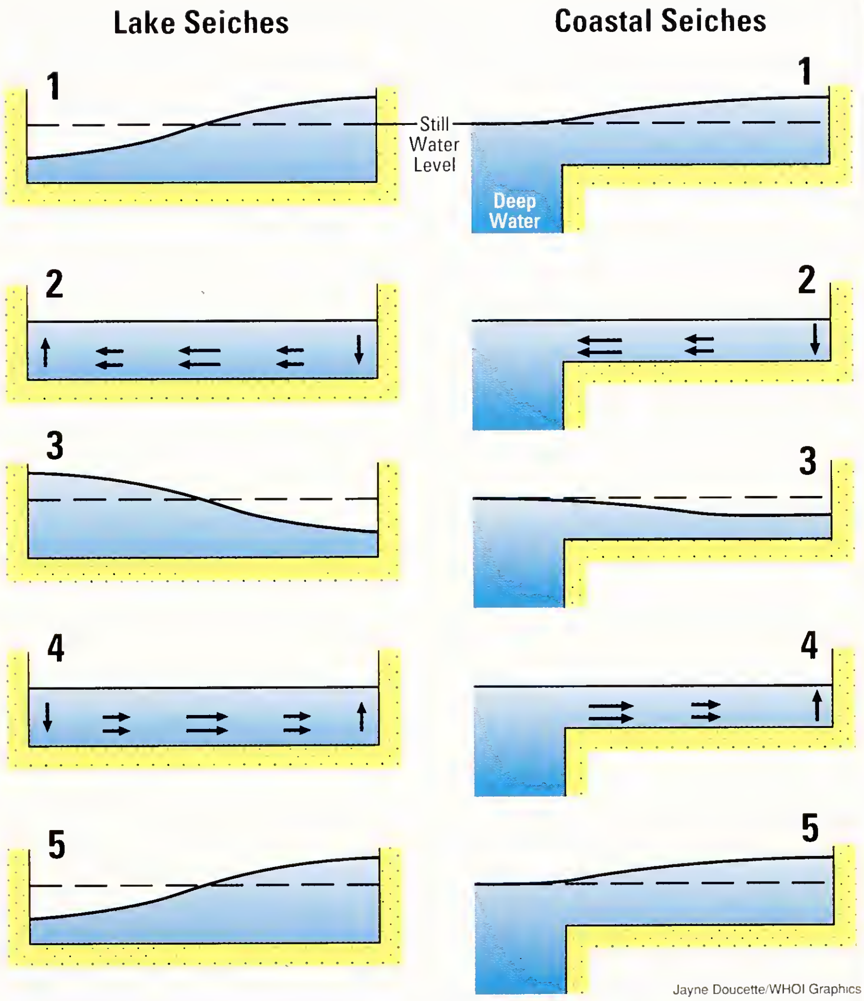
If we plot wave energy on a graph against the period of the waves that occur at a particular coastal location, we expect to see each of these familiar rhythms represented by an energy maximum; a broad plateau in the range from seconds to tens of seconds for wind-generated waves, and high, sharp peaks at about 12 and 24 hours for astronomical tides. In addition, we should not be surprised to see secondary peaks between these expected maxima, peaks of energy representing waves with intermediate periods and produced by other processes.



Coastal wave energy is mostly concentrated at the 12- and 24-hour tidal periods (twin peaks at left of figure) and at the 1- to 10-second periods of wind-generated waves (broad maximum at right of figure). Typically, however, sea-level records from exposed coasts exhibit another energy maximum at periods ranging from 10 to 100 minutes. This energy is largely produced by coastal seiching. Illustrated here is a generalization of the wave-energy spectrum for Cintadella Harbor on Spain's Menorca Island where the dominant seiche period is 10 minutes.

Jayne Doucette/WHOI Graphics

These secondary peaks were once frequently called "secondary oscillations of the tide," particularly by Japanese scientists. The most common are generally produced by standing waves known as "coastal seiches,"which occur at periods ranging from about 10 to 100 minutes. Coastal seiches are typically found in harbors along the exposed coasts of the world. While they are usually small in amplitude compared to local tides, at certain places they can greatly exceed the tidal height and cause considerable destruction. For example, residents of Nagasaki, on the southern coast of Japan, call the half-hourly rise and fall of their harbor's water *abiki*. These coastal seiches can reach heights exceeding 10 feet. Those who live in the Balearic Islands of the western Mediterranean Sea know the local



Jayne Doucette/WHOI Graphics

Seiches are standing waves in basins that produce alternately high and low water levels at the coast and alternately on- and offshore currents away from the coast. Seiches in lakes (left column) were first studied in the 19th century by F.A. Forel who named the phenomenon after the local term for standing waves in Lake Geneva, Switzerland. Coastal seiches (right column) produce maximum currents at the boundary between shallow and deep water (such as the shelf edge or harbor mouth).

10-minute harbor oscillations as *rissaga*, and they are painfully aware of occasions when the *rissaga* rips their boats from their moorings and tosses them together at the harbor head. Other troublesome seiches occur at Capetown in South Africa, at Los Angeles in the US, and at many other locations along the world's coasts.

Seiches, then, are the source of other rhythms known to coastal people—rhythms specific to certain harbors and bays, rhythms that contribute to the mystery of the sea, and, sometimes, to fear of the sea.

Early Coastal Seiche Studies

What produces these sometimes-destructive coastal seiches? One of the first to propose an answer in the scientific literature was Sir George Airy, Astronomer Royal during the reign of Queen Victoria and well known for his development of the mathematical theory describing small-amplitude water-wave behavior. Airy's contribution appeared in a paper published by the Royal Society of London in 1878 concerning tides at the island of Malta in the Mediterranean Sea. Noting the frequent appearance of 21-minute, sea-level oscillations on the Malta tide records and their similarities to records of lake seiches published in 1876 and 1877 by

F.A. Forel in Switzerland, Airy wrote "The origin assigned by Dr. Forel is, I think, most certain; that they are waves originally caused by winds; but that they are reflected from one side and another of the limited sea, and thus become stationary waves. The waves forming the seiches of Malta are reflected, I suppose, from the shores of Sicily and Africa."

In 1907, a little more than a quarter century after Airy's report, R.A. Harris of the US Coast and Geodetic Survey described similar 45-minute coastal seiches at Guanica Harbor on Puerto Rico's southern coast. Like Airy, Harris ascribed the waves to meteorological forcing—strong winds or sudden changes in barometric pressure—but he rejected the concept that the seiches were due to waves reflecting back and forth across the width of the Caribbean Sea (that is, between the shores of Venezuela and Puerto Rico). Rather he proposed that the oscillating water body consisted of Guanica Harbor itself, together with the island shelf bordering the deep Caribbean Basin.

Coastal Seiches in Puerto Rico

Our seiche studies began in the late 1960s when Graham Giese served on the faculty of the University of Puerto Rico and had an opportunity to extend Harris's sieche observations. He examined 10 years of tide-record data from Magueyes Island, which is just a few miles west of Guanica Harbor, but failed to find any correlation between the oscillations and local winds. He did, however, find a completely unexpected, mysterious relationship between seiches and the moon: Seiche activity was minimum at the new and full moon and maximum at the time of half moon, and the half-moon activity was most extreme when the preceding new or full moon occurred at perigee, when the moon was closest to Earth in its monthly orbit.

We had a tentative explanation: Seiches were excited by the arrival of internal waves created by tidal currents.

This correlation strongly suggested a relationship between Puerto Rico seiche activity and the astronomical tides, specifically the semidiurnal tides because only they, and not the diurnal tides, are tied to the moon's phases. But there were two obvious problems with explaining the seiches as being caused by the tides. First, the semidiurnal tide is practically nonexistent along the south coast of Puerto Rico, and, second, the tidal forces are strongest at the time the seiches are smallest—new and full moon—and weakest at half moon when seiches are largest!

There was, however, evidence of a tidally produced phenomenon offshore of Puerto Rico that could be used as the basis of an explanation that would satisfy the observations: internal tides, or, more specifically, internal waves produced by tidal forces. Internal waves occur in the sea's interior, between layers of lighter upper water and heavier deeper water. They travel much more slowly than comparable surface waves—on the order, say, of 5 miles per hour—so that if large internal waves were formed at new or full moon in the southeastern Caribbean offshore of Venezuela and Trinidad where semidiurnal tides are most pronounced, they would arrive at Puerto Rico about one week later, that is, at about the time of half moon.

Can Internal Waves Possibly Generate Seiches?

So here we had a tentative explanation, a hypothesis, for the seiches: They were excited by the arrival of internal waves created by tidal currents in the southeastern Caribbean about a week earlier. But, was it

reasonable to expect that deep-sea internal waves were capable of creating sizable surface waves along the coast? The intuitive answer was no. It was well accepted that strong surface tides along deep-sea margins could produce internal waves, but there was no evidence that the process could be reversed. The accepted pathway for energy transfer was from surface tides to internal waves, somewhat analogous to water flowing downhill.

In 1984, however, David Chapman demonstrated that the process could, in principle, be reversed. Studying a class of coastal surface waves known as "edge waves," he developed a theoretical model showing that deep-sea internal waves impinging upon a steep continental margin could produce coastal edge waves of significant amplitude. In fact, his results indicated that through a process known as "resonant excitation," an example of which might be the proverbial singer shattering a crystal vase, the surface-edge-wave amplitudes could be of roughly the same size as the internal-wave amplitudes.

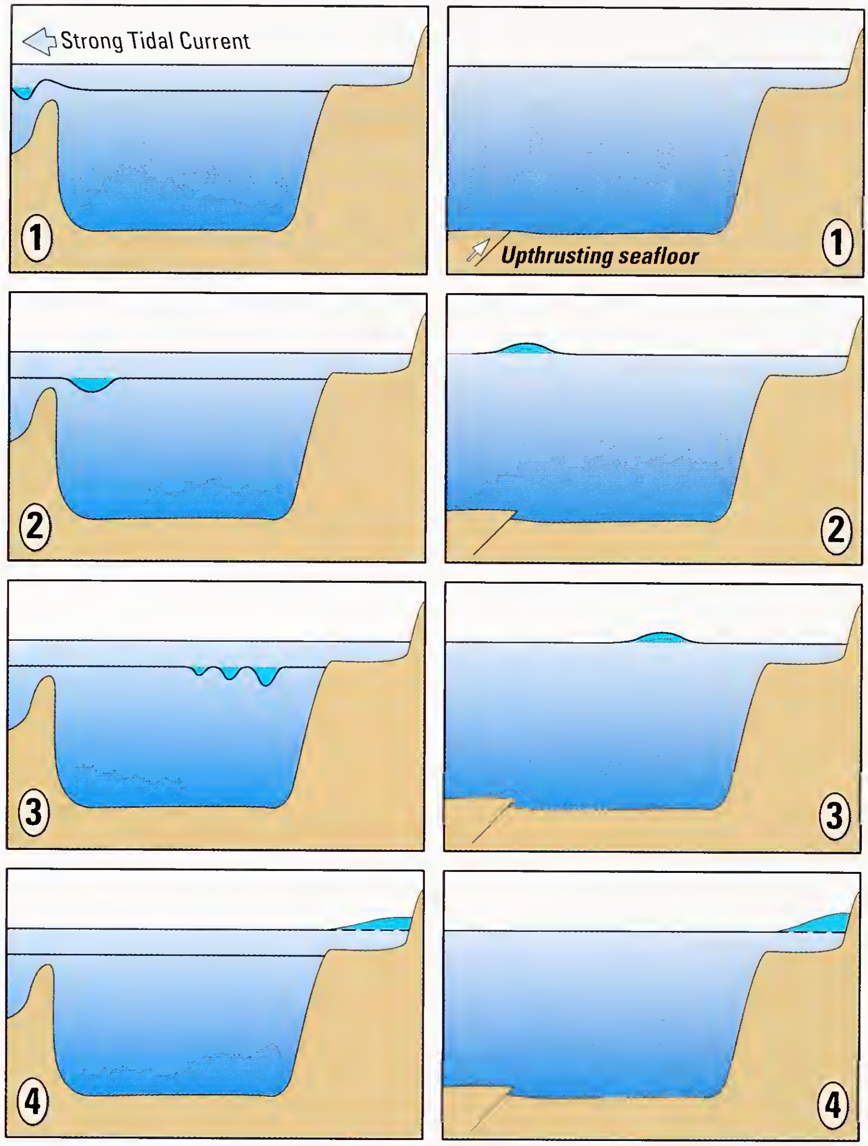
But what about seiches—could the same (or a similar) physical process apply to the generation of coastal seiches by internal waves? This question brought us together. Using the basic theoretical model developed for the edge-wave study and modifying it to match the requirements for coastal seiches, specifically the seiches observed on the Caribbean coast of Puerto Rico, we were able to show that, yes, internal waves of reasonable size arriving at the steep island slope off Puerto Rico could, indeed, produce coastal seiches with the observed characteristics.

Josep Gornes/Courtesy Group of Geophysical Fluid Dynamics, UIB

Large-amplitude coastal seiches can have catastrophic impacts on harbor facilities and small boats. This photograph shows townspeople surveying damage resulting from the large (approximately 2-meter-high) seiches, locally known as rissaga, *that rocked Cintadella Harbor on Spain's Menorca Island in July 1984.*

Do Internal Waves Actually Generate Seiches?

All right, we agreed, this process is possible, but does it really happen? How could we find out? Here we were fortunate to find help in the work of others. A basic assumption underlying our hypothesis was that tide-generated internal waves are capable of carrying considerable amounts of energy over hundreds of kilometers and many days. This had seemed next to impossible until 1980, when A.R. Osborne (Exxon Production Research Company) and T.L. Burch (EG&G Environmental Consultants)



Jayne Doucette/WHOI Graphics

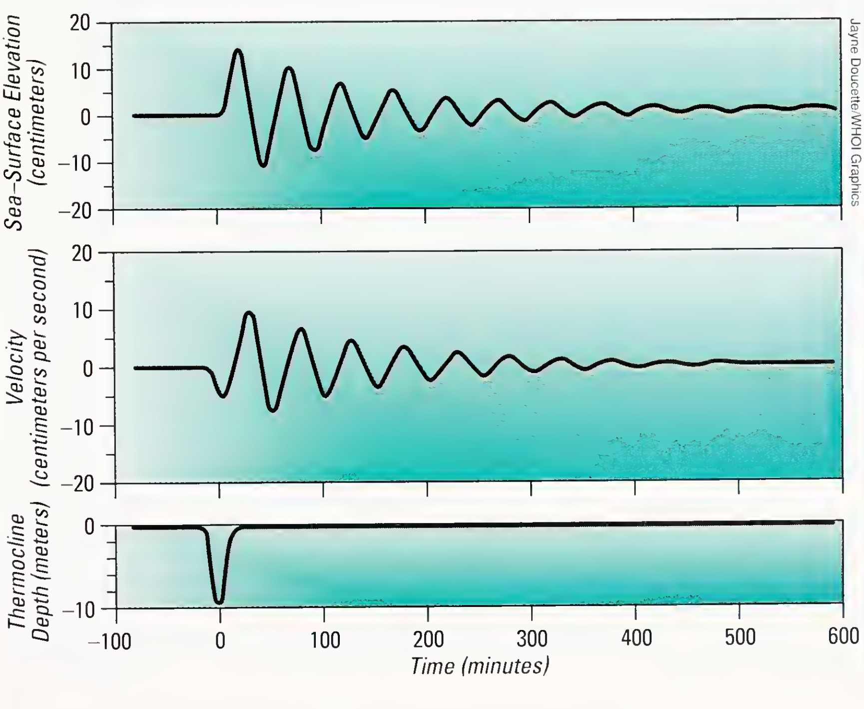
Studies carried out in Puerto Rico and the Philippines support the hypothesis that large-amplitude coastal seiches can be produced by internal waves that have themselves been generated by strong tidal flows of stratified water over shallow banks and ridges. At left, (1) shows an internal "lee wave" being formed by strong tidal currents flowing from right to left. When the tidal current turns (2), the internal wave moves to the right, crossing the ridge to form a broad internal depression. As the internal depression travels away from its source (3), it forms a packet of deep-sea internal "solitary waves." Finally, when the solitary waves reach the coast (4), part of their energy is transferrred to oscillations (seiches) of the coastal water. The total distance traveled by the internal waves may be hundreds of kilometers and may occupy several days. By way of comparison, at right is the related and more-familiar phenomenon known as tsunami, in which deep-sea surface waves caused by submarine crustal disturbances produce seiching in coastal waters. In this case, the total distance traveled may be thousands of kilometers and the travel may be accomplished in hours. While tsunamis may, on rare occasions, produce coastal waves as much as ten times larger than the largest seiches produced by internal waves, the total energy dissipated by tsunamis is much less than the tidal energy dissipated by internal-wave-excited seiches.

provided convincing evidence that large-amplitude, internal, tidal oscillations could exist in the form of "solitary waves" (that is, waves that maintain the almost unchanging form of single troughs for long periods of time), and that discrete packets of such internal solitary waves could travel hundreds of kilometers with little energy dissipation.

Better yet for our purposes, another set of investigators working with John Apel, then with NOAA's Pacific Marine Environmental Laboratories, made a detailed study of internal solitary wave packets that formed at a shallow passage separating the Sulu and Celebes seas in the Philippines and then crossed the entire width of the Sulu Sea to eventually arrive, two and a half days later, at the shores of Palawan Island, some 450 kilometers distant. The opportunity for us was clear: If we could observe seiches along the coast of Palawan, we should be able to tell from the patterns of seiche activity whether or not they were produced by the solitary waves Apel and his coworkers described.

In fact, in 1928 pronounced seiche activity had been reported at Puerto Princesa on Palawan Island by Frank Haight of the US Coast and Geodetic Survey. According to Haight, "The period of this vibration is almost exactly one hour and a quarter...and its amplitude varies from a few hundredths of a foot to 3 or 4 feet." Haight concluded that the seiche forcing could "be traced to atmospheric variations," but he readily admitted that he had insufficient evidence to prove this point.

Supported by an Independent Study Award from Woods Hole Oceanographic Institution (WHOI) and additional funding from the National Science Foundation's International Division, we joined forces with colleagues in the Philippines to establish a tide recorder at Puerto Princesa and to keep it in operation for two years. The Puerto Princesa data provided the supporting evidence we had hoped to find. The harbor experienced the large 75-minute oscillations (seiches) that Haight described; the seiches occurred in fortnightly cycles closely related to the



Results of theoretical modeling demonstrate that a deep-sea internal wave (bottom) arriving at the shelf south of Puerto Rico can produce 50-minute sea-surface oscillations (top curve) and cross-shelf current oscillations (middle curve) similar to those that have been observed.

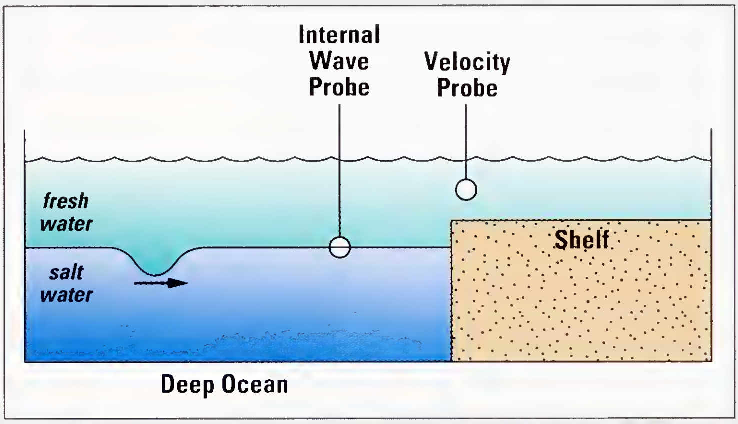
Seiche Experiments

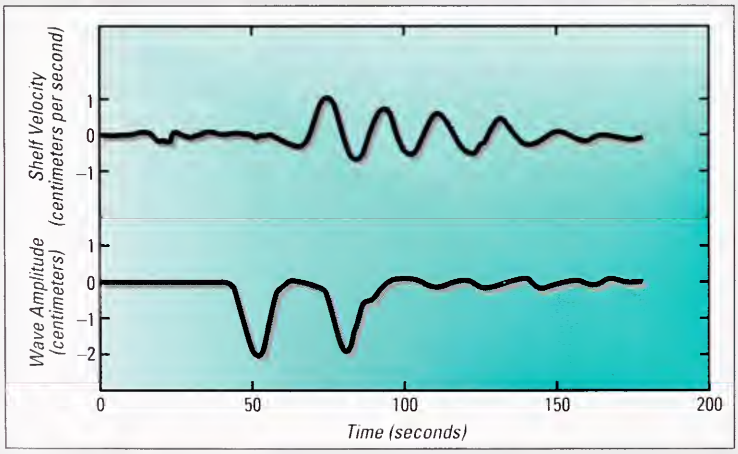
Using observations to directly test a theory is often very difficult. In the case of coastal seiches excited by internal waves, this would require accurate, simultaneous measurement of the ambient stratification, the incoming internal waves, and the resulting seiches. We would then be left with the problem of examining the observations in a way that removes extraneous processes (such as local currents) that are measured, but are not part of the problem at hand. One alternative is to test the theory by comparing it with controlled experiments in a laboratory. Experiments permit us to study just the process we are interested in. Since experiments can be controlled and varied, they can be used to "exercise" a theory, and find out when it works and, just as importantly, where it fails.

In conjunction with the ocean observations described by Giese and Chapman, we have been using laboratory experiments to test our theory of seiche excitation by internal waves. These experiments are performed in an 18-meter-long wave tank that is divided into two sections—a deep area and an adjoining shallow shelf. The bottom of the deep section is filled with salt water. Fresh water floats above this and over the shelf. Using computers to control the experiment, we are able to generate one internal solitary wave that propagates along the tank, reflects from the shelf wall, and excites shelf oscillations. Probes are used to measure the internal-wave amplitude at a point before the shelf wall and the velocity of the fluid on the shelf. An example of one such run is shown. These results can then be compared directly to theoretical predictions. Because we can easily control the experiment by changing the internal-wave amplitude or the shelf geometry, we can test the theory over a broad range of parameters. But perhaps most importantly, the experiments allow us to study more realistic situations, such as a slope connecting the deep section to the shelf, for which there is presently no theory. In this way, laboratory experiments help us to broaden our understanding of the basic physical processes that may result in severe coastal seiching.

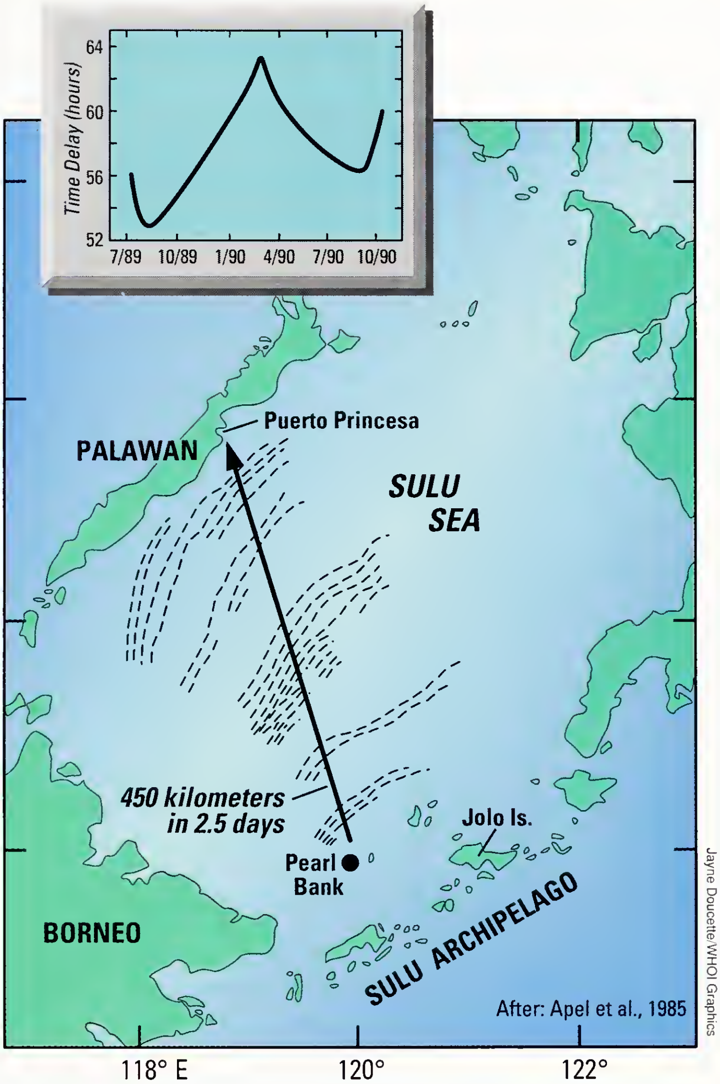
—Karl Helfrich

Jayne Doucette/WHOI Graphics





In the wave tank (top), probes measure the amplitude of waves generated and reflected. The two pulses in the internal wave record are the incident and reflected waves.



Satellite images of the Sulu Sea in the Philippines show the surface expression of internal solitary wave packets initially formed near Pearl Bank in the Sulu Archipelago. After about two and a half days of travel, the internal waves reach Puerto Princesa on Palawan Island, where they produce harbor seiches. The inset shows actual delay times observed during the authors' study.

lunar phases; and the largest seiches began about two and a half days following the strongest tidal currents at the passage where Apel's group had shown the Sulu Sea internal waves to be created.

Is This a Common Global Phenomenon?

Our results from Puerto Princesa confirmed our original hypothesis. Yes, internal waves do produce coastal seiches—in some places. But an important question remains: Is this a general phenomenon to be expected wherever large coastal seiches are found, or is it specific to certain locations where large internal waves are known to occur?

The answer is important because though large, unexpected coastal seiches are known to occur in many harbors around the world, at present they can't be predicted and people who may be affected can't be warned. If, however, it can be shown that these seiches are produced by tide-generated internal waves, it is likely that they will eventually be predictable, as the Puerto Princesa seiches now are.

We have support from the Office of Naval Research to explore the general applicability of our work. Using a combination of numerical and laboratory modeling (as described in the box on page 44 by our WHOI colleague Karl Helfrich) and field work at Ciutadella Harbor in Spain (being carried out in cooperation with scientists at the University of the Balearic Islands in Majorca), we are extending our earlier studies in an effort to make them more generally useful, both to scientists and the general public.

How will this turn out? We don't know. But we do know that no matter how many questions are answered, even more will be raised, for there is no indication that the rhythms of the sea will ever lose their mystery to those of us who live and work along the coasts.

Graham S. Giese is a Research Specialist in the Geology & Geophysics Department at the Woods Hole Oceanographic Institution (WHOI), where he began his oceanography career as a Research Assistant in 1956. His meteoric professional advancement can be partly attributed to his years away from Woods Hole as a graduate student, faculty member, and administrator at various universities and marine research stations.

David C. Chapman is an Associate Scientist in the Physical Oceanography Department of WHOI. He grew up in a rural area of upstate New York before attending Cornell University, where he embarked on a career of mathematically modelling the flow of fluids through trees and other green plants. However, a visit to the beaches of southern California convinced him of the many benefits of a career in oceanography. Reasoning that the ocean couldn't differ much from other fluids, the change seemed natural. Despite this slight miscalculation, he thoroughly enjoyed graduate school (and the beaches) at Scripps Institution of Oceanography, and continues to enjoy studying and living near the ocean.

The Coastal Ocean Processes (CoOP) Effort

Kenneth H. Brink

One definition for "coastal ocean" is the region extending from the beaches out across the continental shelf, slope, and rise. Using this definition, the offshore edge would often be near that of the purely politically defined Exclusive Economic Zone or EEZ (see *Oceanus*, Winter 1992/93, page 7). There is, however, a true scientific cohesiveness to the essentially geological definition above. For example, current patterns over the continental shelf and slope tend to be distinctly different from those of the open ocean, and the consequent shelf physical processes make this region the most biologically productive area of the world's ocean. One economic consequence of this productivity is that 75 percent of the world's fish catch comes from coastal waters—but the importance of the coastal ocean does not end here. The coastal ocean absorbs most of the impact that land-based activities have on the ocean, including river outflow and wind transport of particles and chemicals into the sea. These effects make the coastal ocean important scientifically and economically.

Studying coastal problems requires an interdisciplinary approach.

From a scientist's standpoint, studying coastal problems requires an interdisciplinary approach. A practical example illustrates this point. The Minerals Management Service is responsible for estimating risks associated with drilling for petroleum in US coastal waters. Making such an assessment requires:

• Engineering information—would a spill be likely to occur, given that certain procedures were used?
• Meteorology and physical oceanography—where would the oil go, once spilled?
• Chemical oceanography—how would the oil change with time as it was exposed to the atmosphere and ocean?
• Biological oceanography—what would an oil spill do to living things? and
• Geological oceanography—what would happen to the pollutant once components of it settled to the bottom?

Likewise, many problems of a more strictly scientific character, such as understanding the biological productivity of Georges Bank, require similar combinations of oceanographic disciplines. The coastal ocean exhibits considerable spatial and temporal variability, making most processes dependent in some way on currents. Scientists are finding

Coastal Ocean Processes

more and more that they cannot carry out research in the coastal ocean without involving several, if not all, of the ocean disciplines.

A truly interdisciplinary approach involves organizational complexities, and these have sometimes tended to encourage oceanographers to tackle issues using a one-discipline approach. While this is often sensible, in the end we need to face and resolve the interdisciplinary issues. Two things need to be achieved. First comes coordination, both among scientists and among funding agencies. Coordination among scientists is needed to define and prioritize the problems at hand, as well as to perform the actual multi-investigator research. Coordination among funding and other agencies is required to make optimal use of resources while allowing agencies that have particular goals to accomplish them. Second comes money. Interdisciplinary research, because it involves many investigators and considerable facilities (such as ships), is more expensive than traditional single-investigator science. Getting the money needed for the job requires making a strong case to the funding agencies as well as to the broader scientific community that must be convinced of the value of the proposed research.

The overarching CoOP theme is materials exchange across the continental margin.

Coastal Ocean Processes (CoOP) was organized in early 1990 to address the organizational complexities tied to the well-recognized need for interdisciplinary research in the coastal ocean. After some deliberation, the CoOP leaders defined the general goal to be

> *...To obtain a new level of quantitative understanding of the processes that dominate the transports, transformations, and fates of biologically, geologically, and chemically important matter on the continental margins.*

This is a rather sweeping goal. To give it better definition, the steering committee broke it down into a set of more specific objectives, including understanding of:

- coastal air-sea fluxes and couplings, such as how carbon dioxide finds its way from the ocean to the atmosphere or vice versa,
- fluxes of matter through the seabed, such as sediment deposition or the release of chemicals from the bottom,

• land-derived effects, such as the fate of river-borne nutrients, and
• chemical and biological transformations within the water column, such as how plants grow in response to a chemical change.

Cutting across these ideas are a number of other themes, but the overarching one is materials exchange across the continental margin. This is important because most things of interest vary strongly in the onshore-to-offshore direction (because of landward or open-ocean sources), so that flow in that direction has considerable influence on how these gradients change. It is pressing, too, because physical oceanographers have done quite well explaining alongshore flows, but to date have yet to explain the cross-margin component.

The CoOP organization comprises research scientists at academic and government laboratories, representing the disciplines of marine meteorology and biological, chemical, geological, and physical oceanography. CoOP addresses problems only in basic sciences, although it acknowledges the need to expedite the communication of its results to applied scientists and policy makers who need the new information. Initial funding for CoOP came from the National Science Foundation, but CoOP now deals with several different federal agencies in its efforts to obtain support.

For a new organization, CoOP has proceeded from the planning stage to real research relatively quickly. In 1992, after only about two years of discussion and planning, the first CoOP science project received funding. This group will be studying coupled physical, biological, and geological processes associated with the transport in the water column of larvae from bottom-dwelling animals on the inner shelf (where it is shallower than about 20 meters) off Duck, North Carolina. The inner shelf is one of the most difficult parts of the ocean to study for a number of reasons, not the least of which is that the sea is too rough for a small boat and too shallow for most ships. The first CoOP cruise will use both R/V *Cape Hatteras* (operated by Duke University/University of North Carolina; see inside the back cover) and R/V *Oceanus* (Woods Hole Oceanographic Institution). This will be an arduous and exciting effort, involving new technologies and new approaches to studying the ocean. While other CoOP studies are now beginning to be defined for what is expected to be a four-year program, the inner shelf study is an ambitious first step. ✪

Terri Corbett/WHOI

Senior

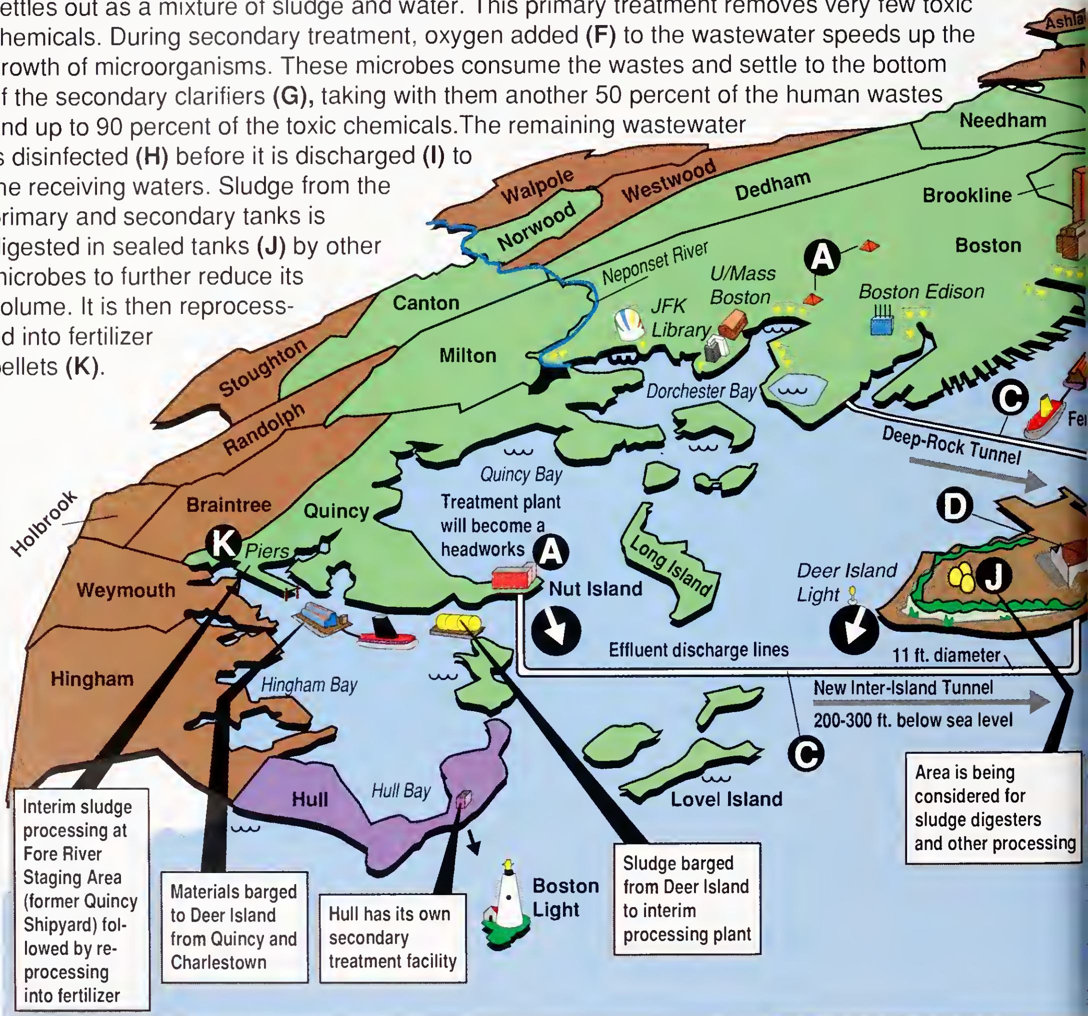
Kenneth H. Brink is ~~an Associate~~ Scientist in the Department of Physical Oceanography at the Woods Hole Oceanographic Institution. He was educated at Cornell and Yale universities. He was a founder of CoOP and is the chair of its steering committee. His research interests include currents over the continental shelf, physical-biological couplings, and the mechanics of steam locomotives. He is perhaps best known for his eclectic taste in neckwear (photo at right).

The official connection, certified Ken

Wastewater disposal is an issue being faced by scientists, policymakers, and citizens around the world. Following are four articles that discuss how this controversial problem is being faced in Boston, Massachusetts. This map provides a reference for these articles.

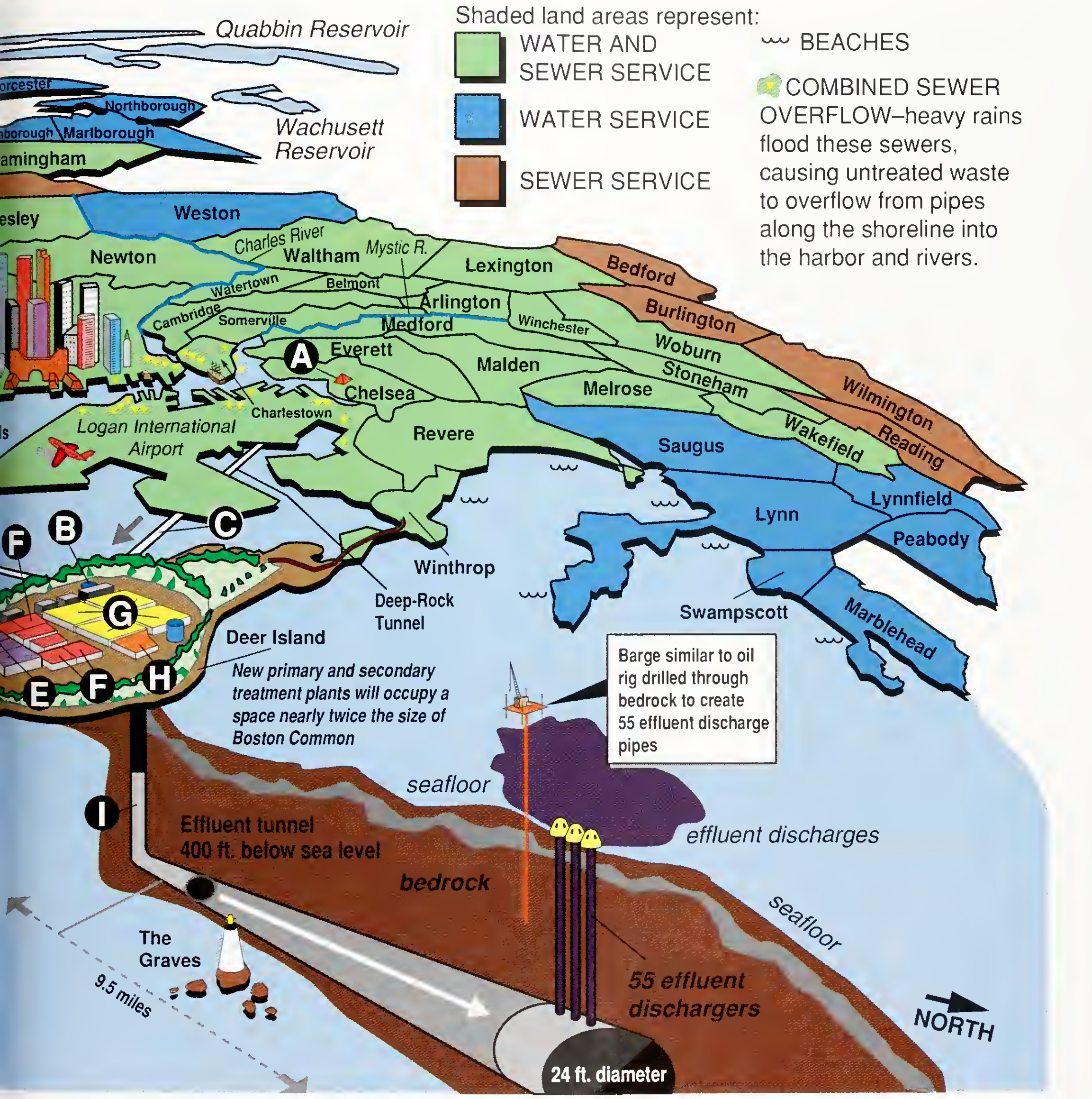
The

Sewage is piped from the communities to several headworks **(A),** where bricks, logs, and other large c are screened out. Pumps **(B)** draw the sewage through deep-rock tunnels **(C)** under the harbor to Deer Island. Mud and sand settle in a tank called a grit chamber **(D)**. Later they are dumped in a landfill for safe disposal. The sewage then flows to tanks **(E),** where 40 percent of the human waste settles out as a mixture of sludge and water. This primary treatment removes very few toxic chemicals. During secondary treatment, oxygen added **(F)** to the wastewater speeds up the growth of microorganisms. These microbes consume the wastes and settle to the bottom of the secondary clarifiers **(G),** taking with them another 50 percent of the human wastes and up to 90 percent of the toxic chemicals.The remaining wastewater is disinfected **(H)** before it is discharged **(I)** to the receiving waters. Sludge from the primary and secondary tanks is digested in sealed tanks **(J)** by other microbes to further reduce its volume. It is then reprocessed into fertilizer pellets **(K)**.



SOURCE FOR ALL GRAPHICS: MASSACHUSETTS WATER RESOURCES AUTHORITY

Boston Harbor Project



James Warren/Cape Cod Times and Jack Cook/WHOI Graphics

"Let's Clean Up the Harbor!"

Massachusetts Water Resources Authority

The new Boston Harbor 24-foot-diameter outfall tunnel has penetrated 1 mile under Boston Harbor. Its 9.2-mile length is scheduled for completion in 1999.

Sounds like a simple rallying cry, doesn't it? Not so when it is Boston Harbor, ultimate receptor of sewage in various stages of treatment for an enormous metropolitan area. Boston Harbor symbolizes the world's beleaguered coastal zones. Mired for decades in the inertia of a once-exemplary bureaucracy, the badly polluted harbor is beginning to recover under the care of a relatively new, but overburdened, agency, the Massachusetts Water Resources Authority (MWRA). The map preceding this page indicates the magnitude of MWRA's responsibility. The next four articles describe the history of the present problem and the ragged legacy of MWRA's predecessor agency, discuss the scientific and administrative issues relevant to the cleanup, look at citizens' roles in environmental issues, make us think about our own responsibility for waste management, and suggest some alternatives to traditional, large-scale sewage disposal.

The Boston Harbor cleanup story begins with the federal Clean Water Act (CWA) of 1972. Until its passage, the law allowed discharge of anything into a water body until the water was polluted, and "pollution" was defined by individual states, whose definitions were driven in some cases by desires to retain or attract industry. The objective of the first CWA was "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters," and it outlined seven "national policy" provisions designed to achieve "water quality which provides for the protection and propagation of fish, shellfish, and wildlife, and...for recreation in and on the water."

There have been several CWA iterations since 1972, and Boston dragged its feet on compliance until it was court-ordered to begin to deal with its polluted harbor. The Boston Harbor waste management system was designed in the mid to late 1980s. Hearings were held, and construction of the $4 billion system is now well under way. But recently, new environmental questions have been raised, and MWRA's ratepayers are aghast when they open bills that in some cases equal their property taxes—and are still going up. Nine suburban communities are suing MWRA because they feel they are paying more than their fair share. One environmental reporter told us he thinks the Massachusetts political culture and citizen protest are "almost over the edge" on the "not in my backyard" syndrome.

The various aspects of the Boston Harbor story bear contemplation. Perhaps their message is that we must all be more aware of our impact upon our environment, that we should not wait for legislative mandates to keep our collective nest clean...that the enemy really is *us*.

—*The Editors*

Sewer Infrastructure

An Orphan of Our Times

Paul F. Levy

The controversy surrounding the siting and use of the 9.6-mile effluent-outfall tunnel from the Boston Harbor Cleanup project is but one chapter in the continuing saga facing the Massachusetts Water Resources Authority (MWRA) as it seeks to repair, rebuild, and upgrade the sewer system serving the Boston metropolitan area. Many people on Cape Cod are averse to the placement of this pipe, fearing negative effects on local water quality. Not surprisingly, the issues they have raised and the political forces they have brought to bear on the MWRA concerning this issue are typical of those the agency has faced on a variety of projects. These battles are inevitable for a public agency involved in building infrastructure projects. A case study of the Boston metropolitan area sewer system illustrates this point.

History Describes a Casual (and Dangerous) Approach

Massachusetts is typical of many states and countries, in that the major sewer systems serving its urban areas were conceived, designed, and constructed in the late 1800s and early 1900s. Public health and safety were usually the impetus for these systems. For example, before Boston had a comprehensive sewer system, there was a less-disciplined approach to wastewater handling. Looking back to the late 1700s and early 1800s, the historian Eliot Clarke observed:

> *The way in which sewers were built at this time was, apparently, this. When some energetic householder on any street decided that a sewer was needed there, he persuaded such of his neighbors as he could to join him in building a street drain. Having obtained permission to open the street or perhaps neglected this preliminary, they built such a structure as they thought necessary, on the shortest line to tide-water.... [By the 1820s] such changes have taken place in the contours of the city, through operations for reclaiming and filling tidal areas bordering the old limits, that, from being an easy site to sewer, Boston became one presenting many obstacles to the construction of an efficient sewer system....*
>
> *As a consequence, the contents of the sewers were dammed back by the tide during the greater part of each twelve hours. To prevent the salt water flowing into them, many of them were provided with tide-gates, which closed as the sea rose, and excluded it. These tide-gates also shut in the sewage, which accumulated behind them along the whole length of the*

Infrastructure: *the basic installations and facilities necessary for the continuance and growth of a community such as roads, schools, power plants, transportation networks, communication systems— and sewers.*

sewer, as in a cesspool; and, there being no current, deposits occurred. The sewers were, in general, inadequately ventilated, and the rise of sewage in them compressed the foul air which they contained and tended to force it into the house connections....

Although at about the time of low water the tide-gates opened and the sewage escaped, the latter almost immediately met the incoming tide, and was brought back by it, to form deposits upon the flats and shores about the city.... Under certain conditions of the atmosphere, especially on summer evenings, a well-defined sewage odor would extend over the whole South and West Ends of the city proper.

It was not just the odor of sewage that was a problem. The growing metropolitan area faced epidemics of cholera and typhoid during the late 1800s. Ironically, this corresponded with the increases in public water supplies that came from water-system expansions in the mid to late 1800s that were not accompanied by adequate systems for disposal of the water once it was used. A series of reports documenting the problem was issued by several towns in the metropolitan area. Along the Mystic River, for example, the Stoneham Board of Health, in a report dated February 29, 1884, noted:

Owing to the introduction and greatly increased use of water, the question of drainage is brought to your attention with redoubled force. A system of drainage for thickly settled portions of the town will soon be a necessity. The sanitary condition of some localities is such as to excite apprehension, if not alarm, and although we have escaped any serious amount of disease proceeding from these causes, we cannot expect further exemption unless these causes are removed.

"The sanitary condition of some localities is such as to excite apprehension, if not alarm...."

Later that year, the Massachusetts Drainage Commission discussed the situation along the Charles River in Dedham, noting:

One marked case of nuisance and pollution exists within the village proper. This is caused by sewage from the county jail, which is discharged into a brook passing through swampy land a few hundred feet distant. This makes a bad stink at times, and it is reported that during the past year several cases of typhoid fever have occurred in its vicinity.

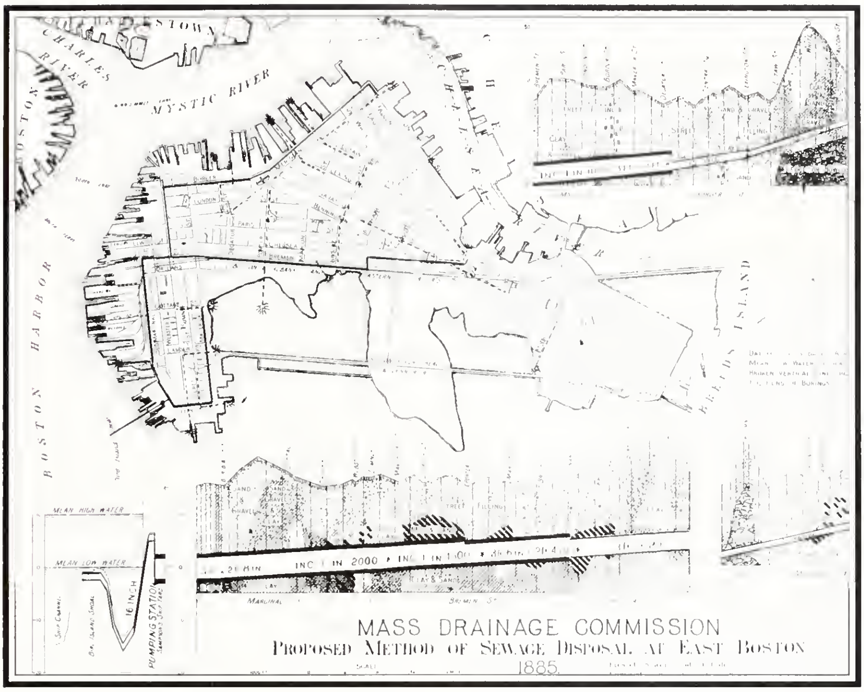
The condition of Waltham's drainage system was described as follows:

After being used and fouled the water is put back into the ground through cesspools and privy vaults. That this disposal of it may in some cases be a source of danger is realized by many persons in the city.

In 1883 the Board of Health said, "No well water in the village can longer be used with safety."

The Drainage Commission report was one of a series of efforts in which the metropolitan area's problems were reviewed. It concluded that a major sanitary engineering project was needed. Confronting the difficulty of this task, the Drainage Commission noted:

Human excrement, from its nature and consistency, is more difficult to handle [than solid waste], and it has been found that the easiest method of getting rid of it expeditiously, before it begins to decompose (that is within 24 hours), is to wash it away through pipes by the aid of flowing water.... By this method, called sewerage, it is easy to move the water and its contained filth away from the houses where it originates. It is not at all easy, however, to find places to put it where it can do no harm.... It is almost impossible to find places where crude sewage can be continuously emptied without doing harm.



Massachusetts Water Resource Authority

In 1885 the Drainage Commission proposed a method of sewage disposal to take wastewaer away from Boston and surrounding communities, and direct it toward Boston Harbor. One hundred years later, the MWRA undertakes the daunting task of cleaning that same harbor.

After reviewing the various technologies available for handling wastewater, the Drainage Commission concluded:

> *To sum up, we are of opinion, upon the whole—*
>
> *1st. That when it can be done unobjectionably, it is best to throw sewage into great quantities of free water.*
>
> *2d. That filtration on land, either alone or in combination with one or more of the other processes, ranks next.*
>
> *3d. That when irrigation is especially favored by circumstances, it is better than either of the preceding; but that it is so seldom that these circumstances can be controlled to advantage, that we assign to it a third place only in practical usefulness.*
>
> *4th. That precipitation and chemical treatment may be advisable in connection with either of the first, second or third of these devices, but in our present state of knowledge ought not to be preferred to either of them.*

These and other recommendations resulted in the construction of a massive collection and transport system, the forerunner of the very system in place today. Its purpose was simple: To take wastewater away from Boston and the communities along the Charles and Mystic rivers out to where it would do no immediate harm, to Boston Harbor. It began with the completion of the Boston Main Drainage System, consisting of tunnels, interceptors, pumping facilities, and storage tanks on Moon Island, from which sewage and industrial waste collected from the city environs were discharged into the harbor on outgoing tides. It was expanded in 1894 to include the North Metropolitan Sewage System, which collected sewage from communities generally to the north of the Charles River and sent it to be discharged off of Deer Island, and in 1904, to include the South Metropolitan Sewage System, which did the same for the communities south of Boston, discharging off of Nut Island in Quincy.

The Metropolitan Sewage Commission was created on June 7, 1889, to design and build this new drainage system. On March 20, 1901, it merged with the Metropolitan Water Board to become the Metropolitan Water and Sewerage Board. In 1919 the Board's responsibilities were transferred to the new Metropolitan District Commission (MDC). As one of the first examples of regional government in the US, MDC was charged with a variety of interrelated concerns: flood control, sewage collection and transport, water supply, parks, and recreation. For years it managed these responsibilities with exemplary competence.

Massachusetts Water Resource Authority

Raw sewage flows into Boston Harbor—one sign of the wastewater system's troubled condition.

But while MDC had a noble history in helping to create regional wastewater systems, something happened in the body politic after about 1960 that caused these systems to be neglected. Simply put, the MDC was not given the resources necessary to maintain the waterworks and sewer system, and consequently the systems began to deteriorate.

Between 1965 and 1985, MDC spent only $11 million per year in capital improvements to the regional water and sewer systems. At this rate of spending, the $2 billion system would be replaced in about 200 years, hardly an appropriate rate for major infrastructure. A more appropriate replacement rate would have been 40 or 50 years. This would have required four or five times the MDC's annual spending. At $11 million per year, the MDC was *falling behind* three or four years for every year that passed. One symptom of this underspending was that the average age of the region's water and sewer pipes exceeded 80 years, and some parts of the system were 140 years old.

The Mandate and the Orphan

Under pressure from state and federal courts, in 1984 the Massachusetts legislature created MWRA to take over the sewer and water system from MDC. It was given a legislative mandate to upgrade and maintain the system, and the power, as an independent authority, to raise water and sewer rates to pay for the necessary repairs. The new authority began its formal existence on July 1, 1985, facing a job of massive proportions. Here are some of the "minor" projects that were waiting on the "wastewater" side of the ledger in 1985.

- Build a new 120-million-gallon-per-day (mgd) sewage pumping station to replace East Boston's 1898-vintage, steam-driven pumping station ($43.9 million).
- Build a new 93-mgd Charlestown pumping station to replace the existing circa-1895 facility ($23.2 million).
- Build combined sewer-overflow screening and chlorination facilities in Dorchester, Somerville, and East Boston ($14.4 million).
- Build a 22.5-kilometer relief sewer system from Dedham to Framingham to stop sewage overflows into the Charles River ($100 million).

• Build an 11-kilometer relief sewer system from Milton to Walpole and Stoughton to stop sewage overflows into the Neponset River ($35.8 million).
• Build relief sewer systems in Braintree and Weymouth to stop sewage overflows into streets and homes in those communities ($45.4 million).

In short, MWRA was facing an immense engineering task when it was created, just to catch up on deferred maintenance. But there was also a need to undertake new projects to bring the metropolitan area into the 21st century, not just to catch up on the last 40 years of the 20th century. The most famous of these is the Boston Harbor Cleanup project, a multibillion-dollar effort to end sewage discharges in the bay.

MWRA also faced an unusual political battle. Recall that it was created under judicial pressure because the usual executive and legislative procedures failed to maintain an infrastructure system that, at first blush, would be in everyone's best interest to maintain. After all, a metropolitan area cannot function properly without a well-maintained sewer system. But the body politic had failed to do its job. According to Bill Geary, MDC Commissioner from 1983 to 1989, it was always possible for him to get legislative appropriations for swimming pools or skating rinks that were not really necessary, but it was virtually impossible to get appropriations for the "invisible" underground infrastructure that was essential to the region's health and well-being.

Massachusetts Water Resources Authority

A surcharging sewer overflows in Norwood, Massachusetts. This sewer is scheduled to be upgraded in the next few years. Meanwhile, heavy rains cause this fountain to occur, thereby allowing raw sewage to flow into the Neponset River.

MWRA then, was created as an "orphan." The legislature knew that the new entity needed broad powers to carry out its statutory mandate. Among other things, it required eminent domain powers to create sewer rights-of-way through private property, and independent rate-setting powers to secure the revenue bonds for capitalizing new investments. It was an orphan, though, because no political figure wanted to take responsibility for its creation or actions. To do so would be to admit the failure of the previous decades, and to take the blame for new siting decisions and higher sewer rates. Both areas were ripe for controversy.

Delving into the Unknown: Siting, and Construction

Infrastructure is real. It takes up space. It has to be put somewhere. Its construction is disruptive. Many people do not want it in their neighborhood, even though it is essential to their neighborhood's existence.

Like other states, Massachusetts has a detailed environmental review process that public agencies seeking to construct infrastructure must follow. The process is designed to publicize the project and solicit public input. Much has been written over the past few years about facility siting, but it remains a difficult area of public policy. Traditionally, public agencies view the environmental review process as something they are required to go through. Likewise, local citizens groups often view the process as a means for blocking a project.

MWRA's philosophy was that the environmental review process was a key part of important two-way communication. It would help educate the public about the need for new facilities, and, equally important, it would

familiarize the agency staff with the types of measures that could mitigate the construction's impact upon the host community. Of course, things did not always work out according to this approach, and there were many instances of intense local opposition to siting decisions. In some of these cases, the agency could only proceed after extensive court proceedings.

But the siting process is only a small part of the infrastructure business. After a siting decision is made, the facility must be built. Even when the siting process went smoothly, problems frequently arose during construction. Here is an example.

One MWRA project was the Wellesley relief sewer extension program: a 11-kilometer, 1.5-meter-diameter pipe designed to end sewer overflows into the Charles River. After spending decades on MDC drawing boards, this project was finally started by MWRA in 1989.

Massachusetts Water Resource Authority

Overflows of sewage into the Charles River prompted MWRA to begin the Wellesley Extension project in 1989.

One section of the pipe had to go through a hill in Dedham. It was not a particularly long section, but much of the hill was made of rock that had to be blasted out, section by section. The broken-up rock (or "muck") then had to be hauled to the surface through the tunnel portal, which was within 60 meters of two houses, including one with a number of small children. Much of the tunnel alignment was near a residential neighborhood.

There was not much choice about how to direct this sewer line. Because of the hydraulic requirements of the sewer, it had to go through the hill, just as the previous sewer, built 40 years ago, had done. The hill was too big to dig the pipe channel from above, and the soil conditions were not right for a tunnel-boring machine. Blasting and hauling was really the only option.

Here is what went wrong. When the first pipeline was built 40 years ago, there were no houses in the area; now, there are several neighborhoods. While the MWRA staff had done a good job explaining what and when things were going to happen, through community meetings and door-to-door visits in the neighborhood, it was not enough. We learned that no matter how much we may prepare neighborhood residents for the noise and vibration associated with blasting, until the real thing starts, they really do not understand how uncomfortable the construction can be.

Pressure from residents led the town's selectmen to limit the project's hours of operation. While this eliminated dinner-time noise, it also made the job last weeks longer than we had planned. This compounded distrust in the neighborhood, because the residents now felt that they could not even believe MWRA projections about the length of a job.

Next we found that petroleum products had permeated rock in the middle of the hill. Nobody knew where they had come from. There was a theory that a nearby church's underground storage tank had leaked, but this was never proven. The state Department of Environmental Protection named MWRA a "responsible party," along with the church.

(Under state law, "responsible parties" are jointly liable for hazardous-waste cleanup costs.) In the meantime, responsible party or not, the agency had to dispose of contaminated tunnel muck, further slowing down the job and adding to its cost.

Shortly thereafter, a local resident complained of petroleum odors in the water from his private well. Ultimately MWRA had to pay to install a pipeline to deliver town water to the affected street.

A different kind of problem showed up in another tunnel segment of the Wellesley extension. In glacial soil, created 10,000 years ago, a mixture of sand, gravel, and small rocks allowed the contractor to use a 1.5-meter-diameter mole to drill a hole and then jack the sewer pipe in behind it. But with less than 30 meters to go after successfully drilling about 800 meters through the earth, the mole met a boulder and could not move forward. It could not move backward, either, because the sewer pipe had been jacked in behind it.

Of course, in accordance with Murphy's law, the mole was stuck about 18 meters under a residential neighborhood. More specifically, it was located 18 meters down, but less than 5 meters away from one house and not far from several others. The solution was to dig an 18-meter-deep trench about 30 meters long, retrieve the mole, and finish the pipe. Before that happened, though, there was an attempt to force grout into the ground to create necessary support for a smaller hole. The soil conditions were such that the grout did not hold, but it took many days of noisy drilling and pumping before that became evident.

This sequence of events created a major disruption in this small section of Dedham, particularly for two women who lived in a house on Commonwealth Avenue. The result was that MWRA had to purchase the home in question.

MWRA workers installing new sewer pipes at this Wellesley construction site encountered numerous difficulties while trying to minimize disruptions to this suburban neighborhood.

Massachusetts Water Resource Authority

There should be one very simple lesson here: Stay away from peoples' neighborhoods. No matter how much you prepare residents for the noise, vibration, and dust associated with heavy construction, it will never be enough. When you mention noise, they imagine one heavy truck driving down their street—not the constant noise of construction punctuated by occasional explosions. There is only one problem with this lesson: When building sewer infrastructure, you *cannot* stay away from neighborhoods. The Massachusetts legislators knew this, and they created MWRA as an orphan to deal with the problem while keeping themselves out of the picture.

How Much Does it Cost to Catch Up?

In 1985, water and sewer ratepayers in the MWRA district paid, on average, about \$140 for service. That yearly price tag is expected to reach \$750 (in current dollars) by 1996 and \$855 by 1998. Two-thirds of these estimated costs can be attributed to carrying out the Boston Harbor project, as determined by federal court. The remaining third is slated for those projects that have been postponed for decades and are no longer discretionary.

There used to be state and federal assistance to help pay for wastewater projects, but those days are past. Both federal and state governments have decided that these infrastructure projects should be self-supporting. There are probably good economic arguments for this, such as ensuring that people understand the full value of the services they are using, but the major impetus for this trend has been political. The state and federal governments have come to conclude that their limited financial resources should be spent on more visible programs and projects, not on the mainly underground infrastructure of the wastewater system. This provided all the more reason for the Massachusetts legislature to create an orphan to deal with the problem.

The Orphan's Tasks

Both federal and state governments have decided that these infrastructure projects should be self-supporting.

Repairing and upgrading the sewer-system infrastructure are essential for the health and well-being of the residents of any metropolitan area, as well as for environmental protection. Notwithstanding these laudatory purposes, infrastructure planning and development is fraught with difficulties for a sponsoring agency. Siting decisions, construction procedures, and rate impacts all offer opportunities for political controversy. This is further complicated when elected officials simultaneously promote the generic benefits of infrastructure improvements while trying to isolate themselves as much as possible from the actual implementation of specific projects. For the foreseeable future, if these necessary improvements are to be made, independent agencies like the MWRA will continue to be forced to "take the heat" for infrastructure projects.

Acknowledgments: Historical sources quoted in this article include Eliot C. Clarke's *Main Drainage Works of the City of Boston* (Rockwell and Churchill, City Printers, Boston, MA, 1885) and the *Report of a Commission Appointed to Consider a General System of Drainage for the Valleys of Mystic, Blackstone, and Charles Rivers* (Wright and Potter Printing Company, Boston, MA, 1886). Additional insights about later years were provided in private conversations with former MDC Commissioner Bill Geary in January 1993.

Paul F. Levy was Executive Director of the Massachusetts Water Resources Authority from August 1987 to February 1992. While in that job, he often said that a measure of his success was how unpopular he was in the community and, by that measure, he was extremely successful. He is currently a visiting lecturer at the Massachusetts Institute of Technology Department of Urban Studies and Planning, and a principal in The Conifer Group LP, a firm offering strategic planning, marketing, and financial advisory services to infrastructure and environmental services companies.

Boston Harbor

Fallout Over the Outfall

David G. Aubrey and Michael Stewart Connor

The Deer Island outfall, an element of the Boston Harbor Project designed to improve sewage treatment services to the Boston metropolitan area, provides an interesting case study of the science and environmental policy issues that surround coastal resource protection. This case includes all the elements typical of complicated public policy decisions: considerations of level of protection, margin of safety, degree of uncertainty, and equity to those accruing the benefits or footing the costs. We explore this case from both the scientific and management perspectives and conclude with suggestions about how scientists and managers can form the partnerships necessary to reach the best short-term solutions while maintaining momentum for long-term improvements.

This case includes all the elements typical of complicated public policy decisions.

Centralized Boston Area Sewage Disposal Began in 1904

Boston Harbor and the major rivers leading into it—the Charles, the Mystic, and the Neponset—have been used for the disposal of sewage wastes for hundreds of years. The backbone of the present system, which collects and transports wastes from the Boston metropolitan area for centralized disposal, was completed in 1904. Since treatment was not available, every day millions of gallons of untreated sewage were simply discharged into the harbor (as Paul Levy describes on page 53).

As it became obvious that these untreated discharges presented health risks to swimmers and shellfish consumers, primary treatment plants were built on Nut Island in 1952 and Deer Island in 1968 to reduce total suspended solids concentrations by 60 percent and organic matter concentrations (such as fecal material) that contribute to biochemical oxygen demand by 25 percent. However, approximately 50 dry tons of digested sludge were discharged into the harbor every day until December 1991. In addition, in wet weather the system's hydraulic capacity (ability of the pipes to carry the water) was exceeded, allowing raw sewage to flow into the harbor through 88 overflow pipes. These combined sewer overflows would occur approximately 60 times a year, dumping more than 10 billion gallons of raw sewage into the harbor each year and causing frequent closings of nearby shellfish beds and bathing beaches. To make matters worse, the Metropolitan District Commission (MDC), the state agency responsible until 1984 for managing water and

wastewater treatment in the Boston metropolitan area, had insufficient funding to maintain and upgrade the treatment plants. Equipment breakdowns were common and resulted in further release of raw and partially treated sewage.

The 1972 federal Clean Water Act mandated an upgrade to secondary treatment (85 percent removal of both suspended-solids concentrations and biochemical oxygen-demand concentrations) for all wastewater discharges from sewage treatment plants by 1977. After fruitlessly exploring several other options of sewage treatment, in 1979 MDC applied for a waiver from secondary treatment as provided by the 1977 Clean Water Act, proposing instead to discharge primary effluent into Massachusetts Bay via a 7-mile outfall pipe, to stop discharging sludge into the ocean, and to abate combined sewer overflows. The MDC studies on water quality claimed that secondary treatment would not achieve significant environmental benefits, and therefore was not cost effective. In June 1983, the US Environmental Protection Agency (EPA) denied the waiver, primarily due to concerns about maintaining the dissolved oxygen standard in the bay and protecting the organisms living in the sediments around the discharge site. MDC then modified its waiver request by relocating the outfall 9.2 miles into Massachusetts Bay to provide better effluent dilution. The application was again denied by the EPA in March 1985. By this time, federal grants for construction of sewage treatment facilities were being phased out; today over 90 percent of the project costs are borne by the local communities.

The city of Quincy and the Conservation Law Foundation (CLF), a public interest group, filed state and federal lawsuits for violations of the 1972 Clean Water Act. As a result, an independent agency, the Massachusetts Water Resources Authority (MWRA), was created in December 1984, to assume control of regional water and sewer services. It was ordered to comply with standards of the Clean Water Act. MWRA, EPA, CLF, and the court established a schedule for construction by 1999 of new 1,270-million-gallon-per-day primary and 1,080-million-gallon-per-day secondary treatment plants on Deer Island, with a 9.5-mile outfall. There were also provisions for solving the combined sewer-overflow problem and for building a land-based sludge processing facility to end the discharge of sludge in 1991.

This court-mandated schedule has brought results. The disposal of sludge into the harbor has stopped, improving the aesthetics of the outer harbor and the "swimmability" of the waters around the outer harbor islands. Sludge is now being converted to fertilizer pellets for commercial use. The outfall and the primary treatment plant are under construction, as well as the first portion of the secondary treatment plant. MWRA's industrial pretreatment and source-reduction programs have significantly reduced the levels of organics and heavy metals in the wastewater. As a result, winter flounder caught in the harbor now show a lower incidence of liver tumors than they did a decade ago. Improvements to the treatment

Wastewater Treatment Levels

Primary
Solids in the wastewater are removed by physical processes such as screening and sedimentation.

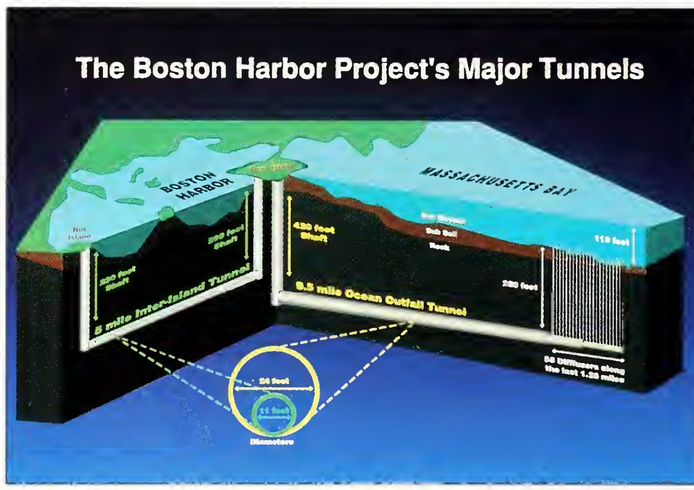
Secondary
Most of the organic matter in the wastewater is removed using biological and chemical methods.

Tertiary
Other contaminants of the wastewater, such as nitrogen and phosphorus, are removed using a variety of processes.

capacity of existing plants have halved the combined sewer overflows, reducing bacterial contamination of the harbor to the lowest levels in 50 years. New overflow treatment facilities have begun operation, and other are being designed. When complete, all of these technical improvements to the wastewater treatment facilities will significantly improve Boston Harbor's water quality.

Recent Questions Raised about the Boston Harbor Project

Recently, the new outfall's proposed placement, 9.5 miles east of Boston in Massachusetts Bay at a 100-foot depth, has caused substantial controversy in the region. Some residents of Cape Cod question MWRA's commitment to implement secondary treatment by 1999, now that Boston sewerage rates are the highest in the country. Some Cape Cod residents even question the sufficiency of secondary treatment to protect the health of Massachusetts Bay. They fear the discharge would cause nitrogen enrichment more than 20 miles away in Cape Cod Bay waters, resulting in nuisance algal blooms and baywide eutrophication that could threaten the North Atlantic right and humpback whales, both endangered species. Some Cape Cod groups have proposed that secondary sewage treatment be augmented so that the effluent is clean enough to discharge through a new outfall into Boston Harbor. A group of Massachusetts Institute of Technology civil engineers has proposed an alternative plan, which suggests replacing the secondary treatment plant with a chemically enhanced primary treatment plant, plus a small secondary treatment plant. They argue that this system is more efficient than the processes currently in use and would reduce the expected costs by as much as $200 million.



Massachusetts Water Resources Authority

Improvements to existing sewage treatment have begun. MWRA is due to complete the Boston Harbor Project by 1999.

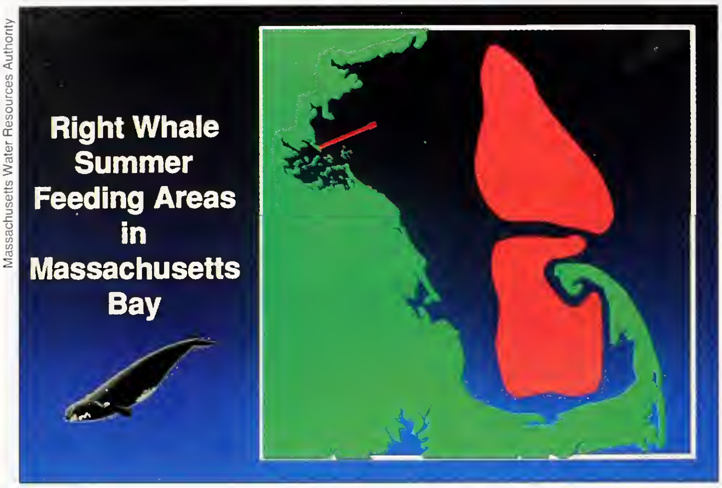
Since there is no conclusive evidence that the water quality standards can be consistently met by the alternatives, EPA has not accepted any modifications to the court-ordered construction schedule, which continues despite the controversies and research on Massachusetts Bay currently under way.

Massachusetts Bay Oceanography

Massachusetts Bay, which encompasses many elements including Boston Harbor and Cape Cod Bay, is a vigorously mixed body of water. Tides and storm winds both provide abundant energy to circulate even the deep water. The twice-daily tidal range averages nearly 9 feet, and currents are correspondingly vigorous, particularly in the shallow waters of Boston Harbor where many inlets constrain exchange to narrow passes between the many Boston Harbor islands. Tidal currents in the region of the proposed outfall diffusers attain speeds of about 0.2 knots on a normal day. Vigorous storm winds strongly affect circulation,

generating currents exceeding those of the tides. These complex currents vary strongly from place to place and at different depths. Peculiarities in the bay's geometry and other physical characteristics create conditions in which surface currents may move in the opposite direction from near-bottom currents during any season.

Another important feature is seasonal stratification. Winter wind mixing is so vigorous and surface waters cool so rapidly that there is little difference between surface and bottom-water temperature. This lack of stratification means that vertical movement of particles such as effluent solids and sediments is relatively unimpeded, and vertical mixing is nearly complete. However, warm summer surface waters create a thermal barrier to vertical mixing: cooler, more dense waters tend to stay near the bottom, while warmer waters are prevented from mixing below the strong thermocline, where water temperatures decrease sharply. These conditions trap treated effluent below the thermocline in the bottom 15 to 20 meters of water during the summer, while in winter the buoyancy of the fresher, less dense water allows the treated effluent to reach the surface waters. This essential component of the region's oceanography is critical to environmental arguments about the outfall.



The federal Endangered Species Act of 1975 mandates that coastal projects be "not likely" to further jeopardize endangered or threatened species. There is some concern that the right whale's feeding grounds may be negatively affected by the outfall. Compare this map with Rich Signell's current model on page 69.

The variety of Massachusetts Bay's habitats and water conditions make it a productive coastal area. It harbors lobsters, fish, and uncountable noncommercial biological resources; elements of the entire food chain from microbes to large marine mammals thrive there in some form. As with most ecosystems, this large marine system possesses some natural equilibrium, which is constantly affected by human activities. These include exploitation of large offshore sand and gravel resources, dumping of uncontaminated sediments dredged from the region's harbors (currently at a location 10 miles east of the outfall site), and overfishing in the region that has changed the food chain—dogfish sharks and rays have replaced cod and haddock gradually during the last decade. How and whether the proposed outfall will further change the balance within this system is fodder for debate.

Phytoplankton, the small floating plants at the lower nutritional or trophic level, are a critical part of the food chain in Massachusetts Bay, as they are elsewhere. They convert energy and food to a form that can be used more easily by higher trophic levels such as zooplankton, fishes, and marine mammals. Altering lower trophic levels can affect the entire food chain. For instance, in the Black Sea, an extreme example, overfertilization by river- and airborne nutrients has completely altered the phytoplankton community. Until the mid-1970s, the Black Sea exhibited a balanced, diverse phytoplankton community. Since then, industrial activities and introduction of chemical fertilizers for agriculture have caused

dramatic increases in nutrient flow to the Black Sea, resulting in increased frequency and intensity of phytoplankton blooms, reduced biodiversity in these same blooms (with only one or two dominant species at present), increased occurrence of hypoxia (low oxygen) due to bloom die-offs, and decreased fishery yields. Massive regions of seagrasses have disappeared, as benthic habitability has declined due to lack of oxygen and other stresses. The community structure of phytoplankton contributes to its utility as food for higher trophic levels; change in structure and diversity may alter the food value even though the total productivity may remain the same.

The impact of toxic algal blooms known as "red tides" may be even more important than general changes to the phytoplankton. The incidence of toxic algal blooms has increased globally during recent decades, though causes for the increases are still speculative. Red-tide blooms in Massachusetts Bay begin at the mouths of Maine rivers and are swept down into the bay by coastal currents. One hypothesis suggests that changes in nitrogen concentrations can stimulate red tides. Other potential causes include high concentrations of iron or dissolved organic carbon. There is no scientific consensus on how best to control these toxic algal blooms.

Several threatened and endangered species inhabit Massachusetts Bay, and other species dependent on bay resources are threatened, endangered, or at risk, including the birds least tern and piping plover. Their protection by the federal Endangered Species Act of 1975 compounds the usual biological questions considered in outfall site selection. The act mandates that projects affecting the coast be "not likely" to jeopardize the continued existence of any endangered or threatened species, or result in the destruction or adverse modification of their habitats. It places a heavy burden on the project proponent to use the best-available scientific evidence in pursuing every possible scientific hypothesis as to how endangered species may be jeopardized. This issue is being addressed on an ongoing basis as we learn more from our studies of Massachusetts Bay.

The possibility of phytoplankton-community change receives added scrutiny because of its importance to endangered species in the bay, particularly the right whale and the humpback whale, which feed directly on the plankton food chain. All involved endangered or threatened species are related at some level to phytoplankton productivity. In addition, recent whale mortalities in the Gulf of Maine have been linked to toxic algal bloom outbreaks.

Though there is no consensus that changes to phytoplankton will occur in Massachusetts Bay as a result of the new outfall, some scientists have raised concerns. Questions include: What nutrient controls are necessary to protect Massachusetts Bay phytoplankton? and Since phytoplankton-community structure can affect all other parts of the food web, can we be sure that analogous cascading events won't happen?

Threatened and Endangered Species in the Massachusetts Bay Region

Endangered

Blue Whale *(Balaenoptera musculus)*
Fin Whale *(Balaenoptera physalus)*
Sei Whale *(Balaenoptera borealis)*
Humpback Whale *(Megaptera novaeangliae)*
Northern Right Whale *(Eubalaena glacialis)*
Kemp's Ridley Sea Turtle *(Lepidochelys kempi)*
Leatherback Sea Turtle *(Dermochelys coriacea)*
Shortnose Sturgeon *(Acipenser brevirostrum)*
Roseate Tern *(Sterna dougallii dougallii)*

Threatened

Loggerhead Sea Turtle *(Caretta caretta)*
Piping Plover *(Charadrius melodus)*

Environmental managers must understand that these uncertainties affect our ability to make clear-cut scientific predictions.

Arguments against the likelihood of such an occurrence include the fact that no additional nutrients will enter Massachusetts Bay: What currently enters nearshore will only enter farther offshore once the outfall is extended. However, there will be technical differences; for instance, secondary treatment changes the outfall form of nitrogen from predominantly organic to predominantly inorganic. The consequences of these subtly changed but continuous inputs are not clear.

The examples given above have a strong "what if" flavor. None of these effects is certain, given present scientific knowledge; similarly, they cannot be totally discounted. Recent-generation computer models that are being applied to the Massachusetts Bay issue will help us answer the questions. They will provide some indication of the detectability of changes in certain "pollutants," such as excess nutrients, within certain distances of the diffuser pipes. So far, the models show that the new outfall will dramatically reduce the contaminant concentrations from Nahant to Hull, while causing little change beyond that region. However, the existing models are limited in that near-field effects, those occurring within some small distance from the diffusers themselves, cannot be predicted with existing physics. It is possible that even a local effect, such as stimulation of phytoplankton growth near the diffuser, could have far-field consequences that must be analyzed. Even the water-quality model, which is being developed to complement the ocean-circulation model, will not be able to answer these questions. Thus, environmental managers must understand that these uncertainties affect our ability to make clear-cut scientific predictions.

The Environmental Management Setting in Massachusetts Bay

MWRA, like any other provider of infrastructure services, is simultaneously considering a variety of challenging issues that have major impact on the public, environmental, and economic health of the region. Outfall siting represents a small portion of a set of complex, interrelated issues including:

- how to ensure that the potable water coming from MWRA reservoirs meets federal standards to protect against water-borne diseases,
- how to ensure that drinking water at household taps meets federal lead-level standards in light of the corrosive nature of lead-free reservoir water,
- how to optimize the treatment of sewage during both dry and wet weather so that water-quality standards are met,
- how to deal with the combined sewage overflows that occur during large rainstorms in order to avoid discharging large quantities of poorly treated sewage to the harbor each year,
- how to replace the leaky, aging infrastructure of sewage pipes (relatively clean water leaking into the system currently accounts for more than half of the water reaching MWRA treatment facilities, as Susan Peterson explains on page 71),
- how to provide redundancy in a water-supply system that currently routes all of metro Boston's water through one aging aqueduct, and
- how to maximize beneficial reuse of sludge products as agricultural fertilizers.

Each of these challenges has a price tag of several hundred million dollars, a constituency that demands immediate action, and potential solutions that are mired in extensive scientific and engineering uncertainty. For instance, MWRA must simultaneously consider complex interactions of whale food chains, the extent to which elevated lead concentrations in water leaving the tap first thing in the morning contributes to blood-lead concentrations in inner-city children, and the probability that the Hultmann Aqueduct, which carries all the water for metro Boston and has been due for replacement for decades, will suffer structural failure. The agency must develop plans for proceeding on all these issues while weighing the portion of its limited total resources that each should receive.

Further complicating MWRA's decision process is the length of time required to proceed from planning to actually operating a facility. The necessary steps include regulatory-review, design, and construction cycles as well as procurement procedures required by state laws. At the system's most efficient, seven years are required to implement a new plan. For instance, MWRA began the process to build new primary and secondary treatment plants in 1986. The primary plant will be operational in 1994; the secondary plant will begin operation in 1996 and be fully operational in 1999. The challenge is to provide a design that allows operational flexibility along with the ability to incorporate new scientific knowledge as it becomes available.

Massachusetts Water Resources Authority

The treatment plant now being built on Deer Island for the Massachusetts Water Resources Authority (MWRA) will discharge cleaner water than the old facility.

The environmental management perspective is different for federal and state regulatory agency administrators, who must weigh outfall issues in conjunction with other Massachusetts Bay pollution-control issues. Bay resource loss has been caused, for example, by coastal runoff that destroyed shellfish beds, habitat loss and overfishing that have reduced fisheries, and historic contamination of urban-harbor sediments that has resulted in fishery closures and had some negative impacts on the food chain.

The toxics issue is declining in significance nationally and locally, because many organochlorine pesticides have been banned from use. In Massachusetts, MWRA is finding that toxic contamination is 5 to 10 times less than it was 10 years ago. Today the major source of toxicity in MWRA's effluent is due to household detergents.

However, the National Research Council's evaluation of coastal pollution indicates that coastal eutrophication is becoming a more serious concern, particularly in areas such as the Chesapeake Bay and western Long Island Sound where nutrient inputs have harmed seagrass beds and crab, lobster, and striped bass fisheries. Most reviews of nitrogen loads, though, suggest that the amount of nutrients entering the Massachusetts Bay system (approximately 10 millimoles of nitrogen per cubic meter per year) is still far less than the amount associated with documented effects (200 millimoles of nitrogen per cubic meter per year).

Scott Nixon (University of Rhode Island), the 1992 WHOI Ketchum lecturer, reached a similar conclusion in a report recently written for Cape Cod's Barnstable County.

One problem facing the regulatory agencies is the extent to which the outfall issue, because of its high level of public interest, diverts public attention from the demonstrated problem of localized eutrophication along Cape Cod's shores. For instance, Brian Howes (WHOI) has measured total nitrogen concentrations in Wellfleet Bay, at the edge of a critical right whale habitat, that far exceed concentrations measured at the mouth of Boston Harbor. The significance of these little-publicized findings to the biology of the bay is not fully understood. Because only a limited number of policy issues can receive attention, focusing the public agenda is often more important than the nitty-gritty details of a particular issue.

Finally, as with many policy issues, science issues may not be particularly determinative of the overall policy decisions. Although the scientific issues that surround the Boston Harbor Project are extensive, the overwhelming lesson is one of the difficulty of maintaining a political will for action. It has been known for more than 20 years that dumping sludge into Boston Harbor was not an appropriate environmental solution; yet, sludge dumping was just stopped on Christmas Eve 1991 because none of the sludge treatment alternatives was without potential environmental concerns, although all the alternatives were superior to dumping in the harbor. The search for scientific certainty can easily become an excuse to do nothing at all.

The search for scientific certainty can easily become an excuse to do nothing at all.

Forging Local and Global Partnerships for Environmental Issues

MWRA attempts to meet the challenge of beginning a project while maintaining an ongoing research and monitoring program by forging research partnerships with local academic institutions and by appointing science advisory panels. For instance, MWRA matches relevant grants scientists receive from several institutions such as the National Oceanic and Atmospheric Administration and the Environmental Protection Agency. Participating institutions include the Woods Hole Oceanographic Institution, the Marine Biological Laboratory, the University of Massachusetts, the Massachusetts Institute of Technology, and Northeastern University. WHOI Sea Grant-sponsored projects include studies of effects of nitrogen-input and sewage-treatment changes on the nitrogen content and nutritional status of coastal waters, the rate of vertical mixing across the thermocline, chemical transport in coastal waters, and contamination of edible marine resources. Additionally, the Massachusetts Bays Program, a joint EPA and Commonwealth environmental planning program, has funded more than $1 million worth of circulation studies, and the Gulf of Maine Regional Marine Research Board is sponsoring a WHOI project on toxic red-tide population in the western Gulf of Maine.

One particularly intensive research effort is being conducted by scientists at the US Geological Survey in Woods Hole, who are building one of the most advanced circulation models ever applied to coastal waters. They are trying to unify the available, scattered Massachusetts Bay observations of mixing and currents into a predictive tool for investigations of outfall impacts on regional oceanography. The model

depicts bay circulation in remarkable detail, though mathematical and numerical approximations still limit the model's accuracy.

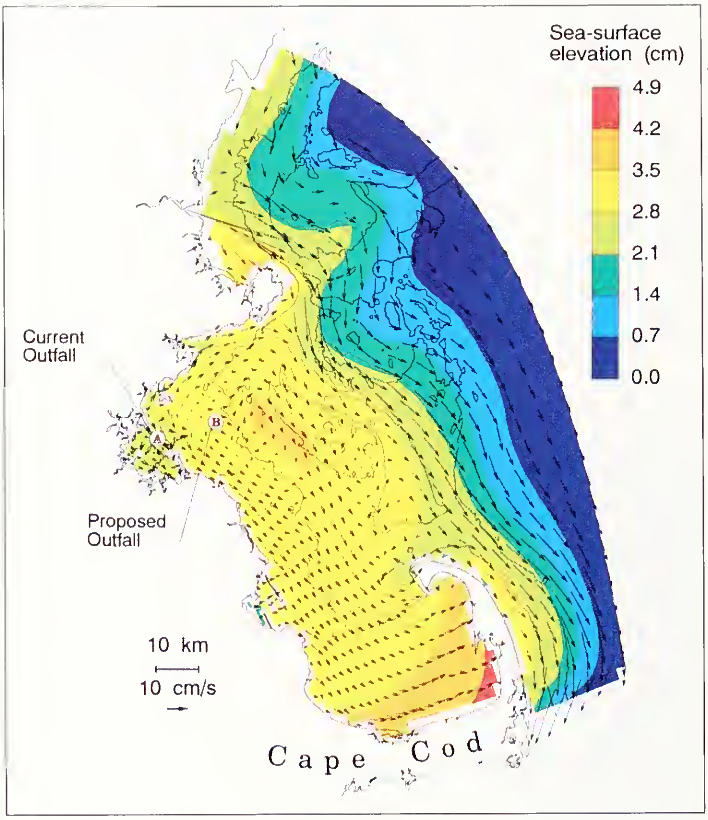
Besides maintaining ongoing research and monitoring, MWRA must also synthesize the findings and relate new information to ongoing policy initiatives. Together, the state and federal regulatory agencies hold several meetings with outside scientific oversight panels each year. In addition, MWRA has convened a group of experts to examine the water quality model discussed above to provide guidance on its application to the bay. These meetings promote the formation of an external scientific consensus about these issues. The nutrient debate has increased the scientific scrutiny afforded these issues and helped spawn some important scientific research in these areas, thanks to support provided by the WHOI Sea Grant Program.

Nonetheless, disagreements persist. Often, there may be substantial agreement on the facts, but very different interpretations of the remaining uncertainty's significance. While governmental agencies may wish that scientific uncertainty did not exist, they must be committed to a full airing of different interpretations of the data. The full spectrum of scientific opinion must be sought. Flexibility in planning must allow for mid-course corrections as new findings occur. At the same time, scientists involved in these issues must be aware that they play several roles simultaneously: wise technical arbiter, advocate for their own position, and potential contractor for future research or monitoring. They must grapple with questions such as:

• How do I justify the significance of my own research interest without creating undue societal fears?

• How can I assure that these issues receive appropriate research attention without over-promising the results' conclusiveness?

• How can scientists' testimony in public forums or in the media receive the same level of peer review and comment as material submitted for publication in the scientific literature?



Richard Signell/US Geological Survey, Woods Hole

This map simulates sea-surface elevation and mean surface currents for December 1, 1990, to March 29, 1991. The model was forced with lunar tides, the Gulf of Maine coastal current, observed time-varying wind stress, and runoff from the Merrimack River. In the western part of Massachusetts Bay, near Boston, there is a region of weak mean flow. The MWRA sewage outfall is currently being extended from the mouth of Boston Harbor (point A) to the middle of this region of weak mean flow (point B). This implies that material discharged out of the proposed outfall will not be swept away by a prevailing current, but will be dispersed and transported by low-frequency fluctuations that have no preferred direction. Once out of the immediate vicinity, however, material will generally travel in a southeasterly direction toward Cape Cod, as it does now.

Other actions are needed in addition to this academic community and government partnering. Since coastal waters are increasingly stressed by human activities, there must be an improved global understanding of coastal ecosystem responses to different types of stress. A rich data base already exists on coastal pollution: Many studies have been performed locally that could contribute to global understanding. Such studies may be limited in scope or by scientific capabilities, but important information can be gleaned from a comprehensive global review. Such a review may be in the realm of intergovernmental bodies, such as the Intergovernmental Oceanographic Commission (IOC) of UNESCO, or the associated United Nations Environment Programme/IOC Global Investigation of Pollution in the Marine Environment. Previous studies, such as those by the Global Evaluation of the State of Marine Pollution group, have identified the coastal areas as critically polluted. However, input-response area relationships have not been sufficiently quantified to enable adequate prediction of responses to pollution.

Scientists must participate more strongly in the decision-making process.

The analogy between the scientific process in the Deer Island outfall debate and the global greenhouse debate should be clear. Scientists have strong reasons to support different sides of the debate, leaving policy makers uncertain about the proper course of action. Rather than voice their concerns and retreat, scientists must participate more strongly in the decision-making process, and contribute ideas on monitoring, mitigation, and triggers, as appropriate. Implementation of such a process will require many changes:

- on the part of the individual scientist who must evaluate personal commitments to societal issues,
- on the part of academic institutions who may have to reconsider their contributions to regionally applied problems (with attendant funding implications), and
- on the part of infrastructure decision makers who must make use of longer lead times to develop scientific consensus and debate, and encourage problems to be addressed from different scientific perspectives in an effort to reduce uncertainties and improve decision making.

David Aubrey, a Senior Scientist at the Woods Hole Oceanographic Institution (WHOI), was thrust into the fray of conflicting uses of the coastal zone because of his interests in nearshore processes, the study of the zone where the pressures of the land meet the continued uprush of the sea. As Director of the WHOI Coastal Research Center from 1986 through 1991, his interests in interdisciplinary science led to continued exploration of the policy and management feedbacks with coastal science. These interests take him throughout the world as he continues to explore the complexities of the global coastal zone.

Mike Connor is Director of Environmental Quality at the Massachusetts Water Resources Authority (MWRA). This article represents his personal views, not the official policy of MWRA. A graduate of the MIT/WHOI Joint Program in Oceanography, Mike became interested in these issues 15 years ago during a WHOI biology seminar that studied solutions to Boston Harbor pollution problems. More importantly, though, the seminar began a long-term collaboration with Christine Werme, and lately their daughter, Janet.

Alternatives to the Big Pipe

Susan Peterson

This article does not have a happy ending. It describes a problem that affects most of the pocketbooks of greater Boston. The problem's history is not unique to Boston, nor is its technical solution. Chosen after decades of angst, a secondary wastewater treatment system and a long pipe to convey treated effluent out of Boston Harbor are now under construction, following a slow, legally and technically convoluted, unimaginative, environmentally and financially unreal process. For there to have been a happy ending, the process would have brought each community to bear responsibility for wastewater treatment, water conservation programs, sewer-pipe maintenance, sludge composting, and effluent discharge, and affordable rates would have enabled the communities to carry out all these responsibilities effectively.

Now Boston has the Big Pipe when we might instead have had the Little Pipe, the Clean Water Pipe, or No Pipe.

The Massachusetts Water Resource Authority (MWRA) wastewater system is a gigantic spider web of pipes that conveys sewage through a treatment plant and currently discharges it into Boston Harbor. As suburban Boston has grown over the past 50 years, towns elected to extend the city sewer pipes rather than build their own wastewater treatment plants. This was a low-cost choice for those taxpayers, but it carried a high cost for the environment (Boston Harbor is one of the most degraded harbors in the US) and for current taxpayers, who must now make up for 50 years of negligence, as Paul Levy describes beginning on page 53.

Our society seems afflicted with a malaise that makes us incapable of dealing appropriately with sewage: Piping it away is the only solution we've come up with. As the volume of wastewater has grown, our solutions have been either a bigger pipe or a longer pipe, or both. The result is that now Boston has the Big Pipe when we might instead have had the Little Pipe, the Clean Water Pipe, or No Pipe.

Going With the Flow: the Little Pipe

We are taught early in life that sewage carries disease, smells bad, and is not a fit topic for polite conversation. Sewage is water contaminated with waste—feces, urine, food scraps, grease, soap, blood, soil, paper, small toys, solvents, metals, cleaners, hair—from houses, businesses, and industries. Most Americans who have overcome their inhibitions and contemplated the subject have focused on the "waste" rather than the "water" component of wastewater. Actually, both components should be minimized.

In the two decades since passage of the Clean Water Act, the US has invested billions of dollars installing and repairing pipes and pumping stations to convey sewage to and from wastewater treatment plants. This activity has moved a lot of water and a relatively small amount of waste from one place to another. Despite the combined efforts of the US Environmental Protection Agency (EPA), state environmental agencies, academics, and civil engineers to improve collection and treatment technologies, most municipal systems are still hydraulically driven to compensate for low flow, peak flow, average flow, and design flow (what the flow will be 20 years from now).

Where does all this flow come from? Some of it is water added to the waste at the source to enable the material to flow. A lot of it is water that gets into the system because the collection pipes leak. The rest of the water, at least in our older cities, comes thundering into the system through pipes that convey storm water through the sewage treatment plant. Allowing rainwater into a sewage treatment plant is illogical and ultimately counterproductive, but the aged systems of Boston, New Bedford, Providence, Chicago, New York, and countless other cities cannot prevent this from happening unless they are redesigned and rebuilt. This is why Boston is constructing a new Big Pipe.

Reducing Wastewater at the Source

A lot of the flow is water that gets into the system because the collection pipes leak.

Source reduction has a wide range of benefits, including water conservation and cost reduction. Most people are aware that potable water is not an unlimited resource and that individual efforts are needed to reduce the demand for drinking water. Conservation also has indirect economic benefits, as it reduces or even removes the need for new reservoirs or wells, water treatment, and distribution systems. Massachusetts has state regulations intended to reduce water use. For example, low-flow appliances are required in all new construction, and citizens are urged to change bad habits by turning off the water while brushing their teeth or washing their cars with a bucket of water instead of a running hose.

In areas where sewer and water bills are based upon gallons actually used, residents can more clearly see the benefits of conservation: less usage = lower costs. Higher water rates and water-conserving appliances can reduce per capita use from 80 to less than 50 gallons per day, with little change in life style. In a city of 500,000 people, that alone would reduce flow to the sewage treatment plant by 15,000,000 gallons per day.

MWRA user fees are assessed per hookup to the water system rather than per gallon used or discharged. Flat fees are less costly to administer, and help to rationalize long-term financial planning. Flat fees also incorporate the fact that while flow may be reduced through a variety of techniques, the waste being carried by the water—the "loading" or "the solids"—remains the same per capita.

There are ways to reduce the loading of every gallon of water entering the MWRA system. For example, it is technically possible to provide tertiary quality septage treatment for all of the homes and businesses in the MWRA network that still rely upon septic tanks for wastewater treatment. Most septage is collected by private haulers (honey wagons) who dispose of the foul, highly concentrated waste material in designated manholes in the sewer system. Since every 1,000

gallons of septage equals about 30,000 gallons of sewage, removing 100,000 gallons of septage every day would reduce the daily load of solids at the Deer Island plant by 3,000,000 gallons. Instead of being added to the Deer Island load, septage could be delivered to one of several dedicated septage treatment plants strung like pearls along route 128. Another way to reduce the load is to ban garbage disposals. These common kitchen appliances add grease and organic loading; prohibiting their use could reduce the volume of solids or sludge by as much as 5 percent.

While conservation technologies can reduce flow, and local septage treatment and banning garbage disposals can decrease loading, one way to reduce both is to remove some towns from the MWRA system. Big towns such as Natick, Framingham, and Walpole could build tertiary treatment systems using any of a range of technologies (including sequencing batch reactors, Solar Aquatics, or rotating biological contactors) at a lower cost per taxpayer than staying in the MWRA system. This would reduce the load on Deer Island's secondary treatment plant and the flow out the pipe into Massachusetts Bay.

Capital and operating-cost savings from reducing loading into the MWRA system are likely to be substantial. A proportional reduction in waste loading by removing septage and ground garbage would not only reduce capital costs, but also lower solids (sludge) handling costs. Nearby Cape Cod Bay would benefit as well, since with reduced loading, there would be fewer nutrients entering the bay via the pipe.

Treatment Technologies

All wastewater treatment relies upon microoganisms in the wastewater to degrade organic material. The three technologies described below each use a different strategy to maintain the microbial populations (biomass) at peak performance.

Rotating Biological Contactors

Rotating biological contactors are large plates or disks threaded on a central shaft, much like a spindle, partly submerged in wastewater. Microorganisms attach to the surfaces of the disks over time and this biomass rotates through the wastewater, coming in contact alternately with the organic material that the microorganisms degrade and the air where oxygen is adsorbed. Occasionally the biomass slough off the disks and become sludge. Rotating biological contactors are most often used for secondary treatment, although they can be used in series to produce tertiary quality effluent.

Sequencing Batch Reactors

Sequencing batch reactors are "fill and draw" tanks operated as follows: 1) fill the tank with raw sewage, 2) aerate the tank, 3) settle the tank, 4) draw off the liquid portion, and 5) draw off the sludge (settled solids) if necessary. The biomass remains suspended in the sludge, available to degrade the next batch of raw sewage. This technology is typically operated to achieve secondary treatment; it can be modified to produce tertiary quality treatment.

Solar Aquatics Systems

Solar aquatics systems combine aquaculture systems with constructed wetlands. These are flow-through systems, housed in a greenhouse, where the raw sewage is aerated in clear-sided tanks and in lagoons planted with a wide range of vegetation. The biomass is maintained on the roots of the plants and in the mixed liquid. Following this step, the partially treated sewage is settled, solids (sludge) are partially recycled and removed, and the liquid portion flows through a construced wetland. These systems produce tertiary quality wastewater.

Reducing the Volume of Wastewater from Infiltration

People are frequently surprised to discover that most sewage pipes leak in the opposite direction to what they fear. They leak *in*. The infiltration of groundwater into gravity sewers both dilutes the waste and increases the flow to the sewage treatment plant by anywhere from 10 to more than 100 percent, depending upon the age and location of the pipes.

Furthermore, most people have been willing to pay for more pipe rather than less, to get the wastewater as far away as possible. Unfortunately, more pipe means more infiltration, which means increased flow to the treatment plant. Given these facts, we pay a high price for our desire to transport the problem rather than solve it.

There are established technologies for installing and maintaining small-diameter pressure sewers, small-diameter gravity sewers, and vacuum systems that are generally less expensive and have no infiltration problem. The existing MWRA collection system is very leaky and poorly maintained (see Sewer Infrastructure: An Orphan of Our Times, page 53). A program of staged replacement and a well-funded and professionally operated maintenance program for the collection system is needed throughout the MWRA network.

We pay a high price for our desire to transport the problem rather than solve it.

Reducing the Volume of Wastewater from Storm Sewers

Storm water falling on greater Boston has few places to go: Most of the soil is covered with paving or buildings, rivers and creeks are channeled, paved, or piped, and many wetlands have been filled for industrial, commercial, or residential structures while others have been dredged to improve shipping channels. The rain sweeps up contaminants from the roads, sidewalks, and ditches, and then flows downhill, flooding manholes, underpasses, and streets. When the catchment basins are full, the water flows to the sewers, to and through the sewage treatment plant, and out the pipe as if through a giant funnel.

Aside from overloading the treatment facilities, this leaky sewer system makes an excellent storm-water collection system, but it has two flaws: it directs flows to only one place, and that is the wrong place. Storm water should be dispersed, not concentrated. Instead of flowing to the sewage treatment plant, storm water should flow or be pumped to swales, bogs, fens, maple swamps, grassy wetlands, and dells, where it can be filtered and treated by soil, roots, stems, and leaves, and their associated microorganisms before it flows into rivers and ponds and ultimately into Massachusetts Bay.

Swimming Against the Flow: the Clean Water Pipe

Under the Clean Water Act, in effect since 1972, we have been guided to design wastewater collection and treatment for high flows and low loadings. The new Clean Water Act (now up for reauthorization) should motivate us to control the flow, reduce water use, encourage industrial pretreatment and reuse, reduce the extent and improve the quality of piping, and build cost-effective treatment systems that treat *waste* rather than funnel *water*.

Traditional wastewater treatment involves solid/liquid separation followed by chlorine disinfection of the liquids. The liquid effluent may be land applied, directly discharged, or piped to a waterway. The solids (sludge) may be composted, burnt as fuel or incinerated, landfilled, land applied, or converted to fertilizer pellets for land application. Until a few years ago, sludge was also dumped at sea.

Considerable progress has been made in the last two decades to improve treatment methods. Modern treatment plants may have multi-

stage solid/liquid separation, aeration to reduce the 5-day Biochemical Oxygen Demand or BOD5, sludge digestion, and chlorination followed by dechlorination. (An index of organic loading, BOD5 is a measure of the amount of oxygen that is consumed in five days to degrade the material. Discharge with a high BOD5 "steals" oxygen from fish and other organisms.) Treatment plants usually remove 20 to 30 percent of the nutrients (especially nitrogen and phosphorus) with the solids; tertiary treatment removes most of the remaining nutrients from the liquid portion.

The treatment plant under construction on Deer Island for the MWRA system will discharge cleaner water than the old facility—secondarily treated sewage rather than primarily treated sewage. But to qualify for the Clean Water Pipe option, MWRA must treat the water to tertiary quality. This seems unlikely given:

- repeated insistence by MWRA, EPA, the House, the Senate, and ratepayers that tertiary treatment is not needed,
- legal and financial commitment to a path with no forks or room to turn around, and
- lack of money.

Even if hydraulic loading could be reduced by 50 percent, there would be additional costs to operate the physical plant to meet tertiary standards.

The standard operating philosophy has been to collect the sewage and pipe it **away.**

Reversing the Flow: No Pipe

During the 1970s and 1980s, we had a "Sewer America" program to get the wastewater from our cities and towns sufficiently treated to meet Clean Water Act standards. The federal government paid for 90 percent of the design, engineering, pipes, treatment plants, and outfall and discharge pipes for these systems. The standard operating philosophy has been to collect the sewage and pipe it *away*—far from homes, neighborhoods, and businesses. Large, centralized plants would then "treat" the water to an acceptable limit, disinfect it, and discharge it to a river, lake, or ocean.

There were some benefits from sewering America: Cities with inadequate collection and treatment systems were able to upgrade to adequate systems, and direct discharges of raw waste into lakes, rivers, and oceans stopped. Large systems were built because community leaders assumed they had only one chance to obtain federal dollars for these projects, so they built in 1975 what they might need in 2015. Expensive systems were built because the municipal portion of the cost was less than 10 percent (sometimes less than 5 percent) of the real cost. The outcome of this (combined with many layers of bureaucracy) was that the close attention to costs that one sees, for example, when a small town buys a new ambulance, did not exist. It was easier to apply for one big grant than several small ones, so centralized systems were preferred over small, community-based ones. This was also under the belief that wastewater could be moved great distances without harm to the environment or the economy.

With major dollars under consideration, conservative design was the rule, and true innovation was stifled. Thus technologies developed and proven in the 1940s and 1950s were redesigned in the 1960s and built in the 1970s and 1980s.

Flow volume is too great in the Boston system for "No Pipe" to be a feasible solution, but it is comforting to contemplate reversing some of the flow. With today's technology, attractive and acceptable treatment plants could be designed for neighborhoods, communities, or towns on the outer edges of the MWRA network to handle conservative flows from homes and businesses. These might include industrial pretreatment, sludge recycling, and water reuse, and they could be esthetically integrated into the environment. Piping wastewater *away* removes the public from the problem-and-solution process, and moving water around costs a lot of money. It would behoove us, then, to keep the water where the people are, instead of expensively sending it into the sea. Local control and the awareness that goes with it would encourage communities to clean and reuse water to recharge aquifers, irrigate fields, and restore ponds and lakes.

Meeting the Nation's Needs for Wastewater Collection and Treatment

Wastewater needs good collection and treatment systems. We need pipes that don't leak and treatment plants that degrade the organic material, remove nutrients, and destroy pathogens without creating chemically contaminated byproducts. We need management systems for sewer pipes, and funding to repair and replace them. And we need to do all this at a price that homeowners, businesses, and industries are willing and able to pay.

It would behoove us to keep the water where the people are, instead of expensively sending it into the sea.

Existing wastewater systems are evolutionary dead ends. Bigger is not better. Collection and treatment costs are skyrocketing, technological and financial innovations are slow to enter the marketplace, water reuse remains rare, and water—good, clean, drinkable water—is wasted rather than conserved. Wastewater needs to be treated on a community basis, so that it can be conserved, pretreated to remove contaminants at the source, and then recycled; the resulting liquid can be used for groundwater recharge, the nutrients for growing plants, and the solids for soil amendment (such as fertilizers and bulking agents).

We are at the start of a new administration that is dedicated to rebuilding the economy. As part of economic development, the federal government, including EPA and the Departments of Commerce, Agriculture, and Interior, needs to incorporate a Water Policy such as that suggested by the Water Environment Federation in *Water Quality 2000* (available from Water Environment Federation, 601 Wythe Street, Alexandria, Virginia, 22314). Such a policy would involve integration of new technologies, ecological principles, and sound public and private finance. Our nation's water system needs help—not just money thrown at it for public works projects, but help in cleaning and restoring the water in ways that are of long term benefit to society and the environment.

Susan Peterson is an anthropologist (Ph.D., University of Hawaii) and farmer (150 acres of lovely New England soil) whose professional career began in Woods Hole 20 years ago. Following more than a decade in the Marine Policy Center at Woods Hole Oceanographic Institution, she taught at Boston University and then founded Ecological Engineering Associates, a for-profit company that sells Solar Aquatics™ wastewater treatment systems to industry and municipalities.

The Role of Citizen Groups in Environmental Issues

Peter Shelley

Citizen groups are spoilers. How often do you hear of a citizen group celebrating the announcement of a new real-estate development, neighborhood solid-waste incinerator, or wastewater discharge pipe? No, they exist only to block these critical monuments to social progress. To listen to some, the country would be a better place without them.

This attitude is simply wrong. Citizen activism is a fundamental aspect of this nation's culture. In environmental matters, citizen advocates play one of the most critical roles in defining, setting priorities for, and resolving the issues of our daily lives. Citizen groups are spoilers, to be sure, but we would all be the worse for the absence of their essential voice.

Citizen activism is a fundamental aspect of this nation's culture.

Boston Harbor is a case in point. From the original Boston Tea Party in 1773, when tax-protesting colonists dumped tea into the harbor, to 1991, when a group of Cape Cod citizens mounted an effort to block construction of an offshore outfall they considered an ecological threat, Boston Harbor has been synonymous with citizen activism.

Reviewing the past 10 years' attempts to reverse the decades-long contamination of Boston Harbor from failing Deer Island and Nut Island sewage treatment plants provides an interesting context for exploring the complex role of citizen groups in contemporary environmental issues.

A private individual, William B. Golden, is generally credited with—or blamed for—initiating the current Boston Harbor and Quincy Bay cleanup, when after a storm he jogged into some excrement washed onto Wollaston Beach. Since the failing treatment plants of the metropolitan sewage system were by that time bypassing billions of gallons of raw sewage and industrial wastes annually, their operator, the Metropolitan District Commission (MDC), was the obvious culprit.

Golden, solicitor for the City of Quincy, Massachusetts, at the time, did not, however, take action as an individual. Instead, he pursued a traditional approach: He brought a nuisance action on behalf of the City of Quincy against the system operators and the Commonwealth of Massachusetts. Indeed, prior to the 1970s, nuisance actions were virtually

the only legal means available for redress of environmental problems; these are very difficult cases and not available to ordinary citizens.

"Public nuisance" actions must involve demonstrable injury to public resources, and they must be brought for the public by a narrowly defined category of public representative, usually the state's attorney general. In such actions, the courts are given the difficult task of balancing the respective rights of the polluter, in this case the MDC, and the victim of the pollution, the public beach in Quincy, here represented by the city officials.

Private citizens have no "standing" to bring such public nuisance actions in court, even if they cannot persuade the necessary "official" to act. Without court access, citizens are constrained to act indirectly through the political process to abate pollution through changes in the law or through politically pressured changes in the regulators.

Role: Enforcing Environmental Laws

It is difficult to overstate the pivotal importance that access to the court system has had to modern citizen-group activism.

Beginning in the early 1970s, public nuisance law diminished in importance when Congress empowered citizen groups through a series of court-access provisions written into federal environmental laws. These provisions allow any person to act as a private attorney general for the US in a "citizen suit," to ensure enforcement of the newly enacted environmental laws. Under a typical provision, the legal action is straightforward: A person files an action in federal court to force a discharger of pollutants to comply with the federal law. The new citizen attorney general only has to meet two criteria: injury, usually demonstrated by damage to some active use of the resource by the plaintiff; and an ongoing law violation, a simple affair because of other provisions that require extensive and publicly available self monitoring. As added enticement, attorneys' and experts' fees can be recovered by a successful plaintiff from the polluting defendant, even including government agencies. It is difficult to overstate the pivotal importance that access to the court system has had to modern citizen-group activism.

The 1983 Conservation Law Foundation, Inc. (CLF) Boston Harbor lawsuit was brought as such a "citizen suit" in federal district court. An unelected, self-described advocate of the public interest, CLF sued MDC and the Commonwealth of Massachusetts for polluting Boston Harbor, and the Environmental Protection Agency for not doing its job as the chief federal enforcement agency.

CLF brought its lawsuit in its own name based on a doctrine known as "association standing," which allows an association with legal status as a person (such as a corporation) to bring a lawsuit on behalf of its membership. Using this doctrine, CLF has appeared as the plaintiff in a variety of cases throughout New England, where it has a geographically diverse membership base.

The impact of CLF's lawsuit on the decades of regulatory delay was immediate. Years of debate and negotiation between federal and state regulators and MDC over the continuing pollution were brought to a halt with the filing of a twenty-some page complaint. Backed by hundreds of pages of MDC-documented federal Clean Water Act violations, the suit's success was a foregone conclusion; only the remedial program and schedule for construction of new facilities would be at issue. Yet

even here, the citizen group, CLF, would be negotiating these items directly with the polluter, not simply powerlessly observing the course of debate between the regulators and the polluter. Access to the courts was power for CLF, and power for a citizen group virtually always translates into action.

> *"[A]ny citizen may commence a civil action on his own behalf...against any person (including (i) the United States, and (ii) any other governmental instrumentality or agency:) who is alleged to be in violation of...an effluent standard or limitation under this chapter...."*
>
> *—Section 505(a) of The Clean Water Act, 33 U.S.C. § 1365*

Role: Forcing a "Hard Look" at Environmental Controversies

Citizen advocacy tends to fall into two categories: broad policy goals and specific project-related disputes. The information requirements for these two categories are vastly different, and a group's understanding of and position on an environmental issue can be completely driven by this difference.

Policy objectives are generally defined by debate, either formal or otherwise, within the advocacy organization or in consensus decisions reached with other organizations. While the scientific and technical sophistication of these policies will necessarily be limited by the sophistication of the participants in the debate, general environmental knowledge and interest are usually sufficient to define and sort out most groups' broad policy objectives.

Issue-specific positions are another matter for two fundamental reasons. First, specific environmental decisions are scientifically or technically complicated—the devil is often in the details. Controlling regulatory frameworks rarely empower an opponent to "just say no." Many environmental problems are difficult—and expensive—to understand and resolve. Second, many citizen-advocate groups are volunteer, ad hoc organizations with scarce financial resources, little technical expertise, and few friends. Unlike membership groups such as CLF, which has a treasury and has been developing staff resources and expertise for over 20 years, most neighborhood groups must start from scratch to raise money and to detail specific objections to a proposal within a narrow 30- or 60-day comment period.

To gain information, groups like CLF can often hire experts on staff or acquire expertise through their board of directors. Smaller groups must often hold bake sales and comb their neighborhoods for local experts. Selling cookies, however, is generally more useful as an organizing tool than for generating the sort of money needed to hire experts in an environmental battle, and "volunteer" experts may be limited, and sometimes unreliable. The answer to this information gap is that citizen groups have become masters at forcing the opposing side to develop the needed information.

A classic example of this strategy is the use of the environmental impact statement (EIS) that is required, under the National Environmental Policy Act of 1969 (NEPA), for federal projects and federally permitted or financed projects like the metropolitan Boston sewage treatment plant. A remarkable legacy of the first Earth Day, NEPA requires preparation of a detailed EIS, most often by the entity that is the potential defendant in a lawsuit. NEPA also requires a "worst case" analysis,

demonstrating that the federal government has taken a hard look at potential environmental problems.

Once prepared, the EIS serves as a "free consultant" to any citizen advocacy group and offers a built-in quality assurance program that creates a catch-22 situation for the agency trying to bury or ignore a stubborn problem. If the EIS is not a serious, hard look at the problem and the agency continues to promote the project unchanged, the project can be stopped under NEPA until the deficiencies are corrected. If the EIS *is* a serious, hard look and the agency elects to continue with the project unchanged, as it can under NEPA, the exposed problems are available as a form of admission in any later proceeding or negotiation about the project under a different law, for example, the Endangered Species Act.

The environmental impact statement serves as a "free consultant" to any citizen advocacy group.

Given this quality assurance aspect of the final document, perhaps the most critical phase of any environmental review is the "scoping session." The quality and usefulness of an EIS is often defined by the predetermination made for each EIS and by the range and nature of the potential environmental, economic, and social issues to be analyzed, known as the "scope" of the review. It is critical that citizen groups participate fully and intensively in the negotiations concerning the scope of an EIS. If a group lacks technical capacity and its funds for experts are limited, their money is perhaps best spent on scope development and review of the draft EIS to evaluate its responsiveness to the scope.

In the case of the Boston Harbor lawsuit, CLF did not have access to any environmental review documents or other information sources from which to build its case against the extended construction program being proposed by the Massachusetts Water Resources Authority (MWRA). Additionally, CLF experienced some difficulty in retaining local engineering and scientific expertise, because most firms were unwilling to bite the MWRA hand that might feed them for years during reconstruction of the metropolitan Boston system.

In order to assemble a team of experts to back up its case that the treatment plant could be built more quickly than proposed, CLF had to retain mostly out-of-area construction contractors and financial consultants. This approach, while it successfully forced the defendants to shave numerous years off the end dates of the construction program, was extremely costly and would be beyond the means of most citizen groups.

Role: Bringing Specific Interests to Abstract Regulatory Proceedings

The federal judicial system has a constitutional requirement that the litigants in federal lawsuits present a real "case or controversy" for judicial resolution. Although there are other jurisprudential and historical reasons for limiting the jurisdiction of federal courts in this manner, the most-often stated justification for the "case or controversy" requirement is insuring that the court is presented with concrete facts by advocates who have an obvious stake in the outcome. Hypothetical or speculative interests are not sufficient to insure that the matter will be energetically argued and "justice" done.

Regulatory actions have no such "case or controversy" requirement. While a project proponent assuredly has a palpable stake in the specific outcome of, say, a permitting decision, the regulators do not. Their

interests lie in more generalized program policy and bureaucratic matters. In addition, the "revolving door" phenomenon is well established in the environmental regulatory world; regulators and consultants often have long-term personal or professional connections independent of the particular matter under review. While such collegial relationships often facilitate review interactions without any compromise of project quality, they also create the potential for conflicts of interest for the regulators. These conflicts need not always involve the exchange of money or promises of future employment in return for valuable regulatory treatment; they can consist of a simple inclination to protect a professional friend from any criticism or scrutiny of an analytical deficiency or defect.

Citizen groups change the regulatory dynamic radically. The local and specific interest in neighborhood that is pejoratively labeled the "not-in-my-backyard" syndrome is, in fact, critical if regulatory justice is to be done. This natural and very real "backyard protective mechanism" provides citizen advocates with the specific adverse interest that so often is lacking between permit applicants and regulators. Citizen groups, accordingly, play a legitimate and fundamental role in these proceedings by holding the feet of regulators to the fire, albeit only figuratively, and producing a result that better represents a fair legal, as well as social, solution.

This aspect of citizen advocacy can be clearly observed in the case of Boston Harbor. CLF, as the citizen advocacy group plaintiff attempting to bring MWRA into compliance with the Clean Water Act, did not have a particular stake in how that compliance was accomplished, and decided early in its involvement to remain as neutral as it could on permitting matters, consistent with insuring that MWRA achieve a sound environmental result, on schedule. In communications with other advocacy groups around Massachusetts Bay and in MWRA's service territory, CLF made this position clear and indicated that other groups would have to be responsible for raising specific challenges to the remedial program elements. Like the elephant in the Chinese proverb, it was clear that the massive MWRA project would look very different to

The groups mentioned in this article are in Massachusetts. All are membership-based.

APCC: Association for the Preservation of Cape Cod
is an Orleans-based group with a mission to protect and preserve Cape Cod's natural resources and environment.

Center for Coastal Studies of Provincetown
is an independent organization dedicated to research, preservation, and intelligent use of coastal resources through conservation and public education.

CLF: Conservation Law Foundation
uses law to improve resource management, environmental protection, and public health. Offices are in Boston, Montpelier, Vermont, and Rockland, Maine.

Save the Harbor/Save the Bay
formed to foster a positive vision of Boston Harbor and Massachusetts Bay, and to help restore and protect these waters.

SOB: Save Our Beaches
was an active 1980s advocate for coastal resource protection, especially of the Massachusetts and Cape Cod Bay shorelines south of Boston.

STOP: Stop The Outfall Pipe
is a West Dennis group that organized to halt construction of the MWRA outfall.

SWIM: Safer Waters in Massachusetts
is an advocacy group at the Northeastern Marine Science Laboratory that focues on Nahant's nearby waters and natural resources.

different groups based on their geographical and programmatic perspectives, and CLF resolved to let these groups "carry their own water."

Such regional concern first arose about the massive treatment plant outfall location during the early stages of the facilities planning process in 1986. SWIM, a Nahant citizen group, had already suffered decades of pollution as material from the Deer Island plant and the Inner Harbor followed currents northward from time to time and degraded SWIM's "backyard." The location of the new outfall pipe was of obvious concern to these citizens, who immediately joined the debate. Soon SOB, representing residents of the southwestern shore of Massachusetts Bay, joined SWIM. These groups wanted the outfall moved farther offshore.

These groups have accomplished three concrete objectives that are likely to improve the project's overall impact.

Their effective lobbying and scientific sophistication (supported by scientists from the Northeastern University Marine Sciences Laboratory in Nahant) as well as their mere presence during facilities planning ensured that MWRA consultants and federal and state regulators considered the full range of potential impacts at a number of locations, and then carefully documented the final selection. Although the final site selection can also be explained on technical grounds, it is probably no coincidence that it is roughly equidistant from Nahant and the southwestern shore, and far, although not the farthest possible, from land into Massachusetts Bay.

In order to fully appreciate the impact of this citizen role on decision making, one only has to reflect on the interests that were not concretely represented in these early phases of the outfall siting decision, namely, Massachusetts Bay and Cape Cod Bay. The baywide advocacy group Save the Harbor/Save the Bay had just been formed, and was still very much in its infancy during the early stages of outfall planning. The rich marine resources of Stellwagen Bank were unrepresented. Finally, many of the Cape Cod groups who presently figure significantly in the outfall siting debate either didn't exist, as in the case of STOP (Stop The Outfall Pipe), or were unable to participate because of resource limitations.

Partly because of the sequencing of regulatory actions, but also quite clearly because of the absence of any participation by advocates attempting to represent the environmental interests of the eastern and southern resource areas of Massachusetts Bay, early facilities planning was limited in terms of its analysis of the outfall pipe's potential impacts on endangered species, on Stellwagen Bank, on toxic algae, and on Cape Cod Bay resources.

By 1993, that dynamic has changed dramatically. SWIM and SOB are now in the background of the public debate as the outfall moves into serious construction. Current debate is being driven by a different mix of citizen and other advocates, from the extreme position of STOP, whose constituents call for cessation of outfall construction, to the Center for Coastal Studies, the Association for the Preservation of Cape Cod, and Save the Harbor/Save the Bay, groups that have continuing concerns about the wisdom of an outfall pipe in Massachusetts Bay and the use of dilution to reduce the impact of pollutant loadings.

From the perspective of these groups, the MWRA outfall is simply a mechanism to export pollution from Boston Harbor into Massachusetts Bay without proper treatment, at the expense of bay resources. While the "truth" regarding their point of view may never be known as scientific fact, regardless of whether the outfall comes on line as presently proposed or is moved, these groups have accomplished three concrete objectives that are likely to improve the project's overall impact.

First, they have forced the regulatory agencies to focus specifically on four issues that were not thoroughly analyzed in the original documentation: the impact of nutrients from the 400 million-gallon-per-day (average) effluent flow on the bay's food chains, the bay's geophysical circulation patterns, the effect(s) of the effluent on endangered species, and the design and implementation of an adequate monitoring program. Second, they used their political strength to force the state to allocate funds to the politically neutral Cape Cod Planning Commission for the express purpose of hiring experts to critique the analysis of these issues on behalf of Cape Cod. Third, they forced Congress to authorize $1.2 million for a federal study of the nutrient and physical oceanography questions presented by the outfall siting.

These maneuvers—successful as a result of both the groups' political power and the underlying merits of the issues—solved the groups' informational limitations while insuring that the agencies took a "hard look" at the hard problems. Ultimately, the "outside" consultants may even be called as expert witnesses in a court action challenging the outfall decision when final outfall permits are issued, particularly if the technical comments are not seriously considered or adequately addressed in the administrative record.

Role: Educating the General Public

Citizen-group action on Boston Harbor issues has generally raised public awareness of the environment and of human impact on it, especially in Massachusetts Bay. How was this accomplished? Press coverage. It is no secret that the press responds most quickly to controversy, particularly public controversy. While the periodic reporting of a boiling environmental controversy is no doubt inferior as an educational forum to sitting in a laboratory or a classroom, the truth is that most people are educated about the environment by the popular press.

While disagreements and scientific debates between MWRA consultants and regulators or the professional staffs of groups like CLF are virtually daily occurrences in any large project, they simply are not newsworthy. For most reporters and their readership, such esoteric exchanges—notwithstanding their technical value and environmental importance—are simply boring or unintelligible. Distribute a press release saying that the MWRA outfall threatens whales, however, and reporters will be at the door. Citizen groups are intuitively brilliant when it comes to framing the public debate over environmental issues through their access to the press and the "newsworthiness" of their

positions. This is a serious responsibility, and, for the most part, it is taken very seriously by all effective citizen advocates.

The press's educational function is also taken very seriously by most environmental reporters. Certainly, they want to write a good story, particularly if it involves political ego-busting, but most reporters also want to tell a complete story and will make a strong effort to include its various sides. In the process and over time, the general public becomes informed and educated about environmental issues.

Citizen groups, then, *are* spoilers: They disrupt the smooth unfolding of carefully designed and expensively developed project timelines; they often can't get their collective acts together until the last minute when it is late in the game to make fundamental project changes; they say things in the press that are not always flattering or, sometimes, even accurate; they seem to have disproportionate political and legal power; and their positions are sometimes plain wrong with regard to the law and the science.

Similar observations could be made about anyone and any group. In the main, citizen groups play an indisputably positive and indispensable role in environmental policy formation and decision making in this country:

- They make sure that laws are enforced.
- They require project applicants and regulatory agencies to take a serious, detailed look at environmental issues, particularly those that cannot be reduced to simple equations.
- They bring specific and concrete interest and passion to abstract regulatory proceedings.
- They educate the general public about the nature of environmental decisions and the environment itself.

In defense of a resource, citizen advocates are not afraid to challenge convention or fancy facades.

In a world of scientific, technical, and political uncertainty, what more can be asked? With limited funding, volunteer staffing, and often (shudder) no advanced academic credentials, citizen groups must fumble around a good deal in the beginning of a public debate. On the other hand, citizen groups, especially the good ones, have an unerring eye for the Achilles heel of any project; in defense of a resource to which they have every right and reason to lay special claim, citizen advocates are not afraid to challenge convention or fancy facades, no matter how elaborate or well-intentioned. That they do this in defense of their "backyard" is irrelevant: What higher stake would anyone seeking the best result ask a player to bring to the table?

Peter Shelley is a Senior Attorney at the Conservation Law Foundation in Boston where he is Director of the marine and water programs and serves on the management group. He has been muddling around with environmental law and policy since 1978 when he graduated from the evening division at Suffolk Law School, where he degraded much of his already-limited gray matter. A student of Zen Buddhism, Peter practices a form known as zazen-nodishdo, *that is, the art of using meditation to avoid household chores.*

NOAA's Coastal Ocean Program

Science for Solutions

Lauren Wenzel and Donald Scavia

The year 1988 was not a good one for the coasts. Hundreds of dead and dying dolphins washed ashore from unknown causes; medical wastes, including syringes, appeared on New Jersey beaches; and many areas were too contaminated to permit shellfish harvesting or swimming.

People responded to this visible evidence that the coast was in trouble. Congressional committees held hearings to find out what was causing the problems, and what could be done about it. *Time* and *Newsweek* featured cover stories on "Our Filthy Seas," advising, "Don't Go Near the Water." Many problems that drew attention that year were symptoms of longstanding patterns of human activities near the coast. And some, such as the pollution of beaches by sewage outflows, could be addressed by available technology and management decisions. Others were, and are, more complicated. The depletion of US fisheries continued, reaching crisis proportions in some regions, due to the inexact nature of stock assessments and the social and economic consequences of imposing restrictions. For other issues, such as the contamination of estuaries and coastal waters by toxics and nutrients, the sheer complexity of the problems frustrated managers looking for solutions.

COP focuses coastal ocean science efforts on emerging and longstanding problems.

Congress responded by passing legislation to control ocean dumping and medical wastes. Looking at the broader set of coastal issues, the National Oceanic and Atmospheric Administration (NOAA) created the Coastal Ocean Program (COP) in 1989 to focus NOAA and academic coastal ocean science efforts on emerging and longstanding problems.

Today, the coastal ocean's troubles are, if anything, more formidable and complex than they seemed even four years ago. Toxic algal blooms, bringing public health concerns and severe impacts on coastal tourism, have become increasingly common, yet are still poorly understood. Hurricane Andrew, with an estimated $20 billion price tag, vividly illustrates the economic impacts of tropical storms along our coasts. And even toxics banned years ago, such as DDT and PCBs, continue to accumulate in fish and shellfish, threatening human, wildlife, and ecosystem health.

Within NOAA, COP has become a focal point for developing the scientific information needed to predict, and, where possible, prevent or

CoastWatch allows managers and researchers to obtain satellite and in situ data far more quickly and easily than in the past.

mitigate negative human and natural impacts on valuable coastal resources. From its inception, COP was designed to "cross-cut" the agency to work effectively with all of NOAA's offices. To provide scientific information on a wide range of issues, the program aims to improve predictions of:

- fishery stocks for better conservation and management of living marine resources,
- coastal ocean pollution to protect and restore environmental quality, and
- coastal hazards to protect life and property.

This cross-cutting approach allows the program to adopt a broad, integrated perspective on coastal issues. COP has also acted as a catalyst for enhancing NOAA/university partnerships, bringing agency and academic scientists together to coordinate their investigations on important issues. COP represents a stable yet flexible approach to scientific research on critical coastal issues. Rather than attacking each problem piecemeal, the program supports research toward fundamental advances in our ability to predict environmental conditions and changes.

In the three years since COP began, the program has made significant contributions to our understanding of coastal processes and ecosystems in seven "theme" areas: nutrient overenrichment, toxic chemical contamination, coastal fisheries ecosystems, estuarine habitats, coastal hazards, CoastWatch, and information delivery. In addition to the research discussed below, COP supports the development of sensitive indicators of toxic contamination, models to predict flooding from storm surges, and research dissemination efforts to ensure that critical research reaches coastal managers.

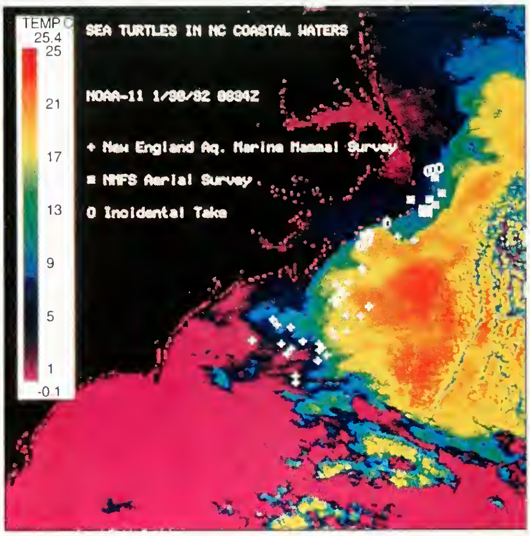
CoastWatch Delivers Data Rapidly Where It's Needed

While NOAA has long had an impressive ability to gather information about the ocean's surface through satellites and aircraft, these data were often stored thousands of miles from the areas they pictured, reaching the local managers and researchers who needed them weeks or even months after they were collected. To solve this problem, and put the agency's considerable information resources into the hands of those who need them, NOAA conceived CoastWatch. A system of regional data-access sites, supported by a central data processing and distribution center, CoastWatch allows managers and researchers to obtain satellite and in situ data far more quickly and easily than in the past.

CoastWatch was first applied in 1987 when National Marine Fisheries Service scientists at Beaufort, North Carolina, found that sea-surface temperature maps derived from NOAA's polar satellites could be used to analyze oceanographic conditions associated with an offshore harmful algal bloom. The bloom, which lasted for three months, destroyed nearly half the state's scallop population, and forced the closing of all shellfish beds, although not before dozens of illnesses were reported. Fishery and tourism losses rose to $25 million. The blooming dinoflagellate (*Gymnodinium breve*) was a species native to the Gulf of Mexico but new to the Atlantic, carried by the warm waters of the Gulf Stream. After the bloom subsided, researchers reviewing satellite data from that period found that a breakaway stream of warm Gulf water had snaked its way off the Cape Hatteras coast, bringing the bloom with it.

While CoastWatch's pilot application was too late to prevent seafood poisonings in 1987, it now provides near real-time products to monitor and predict such disruptive events. CoastWatch data are used across the country for a wide range of research and management applications. In California, the CoastWatch node tracked coastal ocean responses to 1992 El Niño conditions (see *Oceanus*, Summer 1992). Fisheries managers received critical information. El Niño brought warmer waters inshore, creating conditions that are believed to benefit subtropical fish at the northern end of their range and a detriment to stocks at the southern end of their range. Anomalous fishing conditions have also been detected in the Gulf of Mexico by fisheries managers using CoastWatch data. In the Great Lakes, CoastWatch data is part of the Great Lakes Forecast System, a linkage of observations and models that will provide coastal planners with forecasts of winds, waves, water levels, and temperatures throughout the region. In the Northeast, CoastWatch data have been used to track "red tide" blooms, and to study the oceanic aftereffects of Hurricane Bob.

New remote sensing technologies present another opportunity for coastal researchers and managers. In 1993, a new satellite will be launched with an ocean color sensor, SeaWiFS (Sea-viewing Wide Field-of-view Sensor), capable of measuring spectral radiances at the ocean's surface. SeaWiFS data can be used to estimate phytoplankton biomass and productivity on a variety of scales. COP will support the development of coastal ocean and Great Lakes applications.



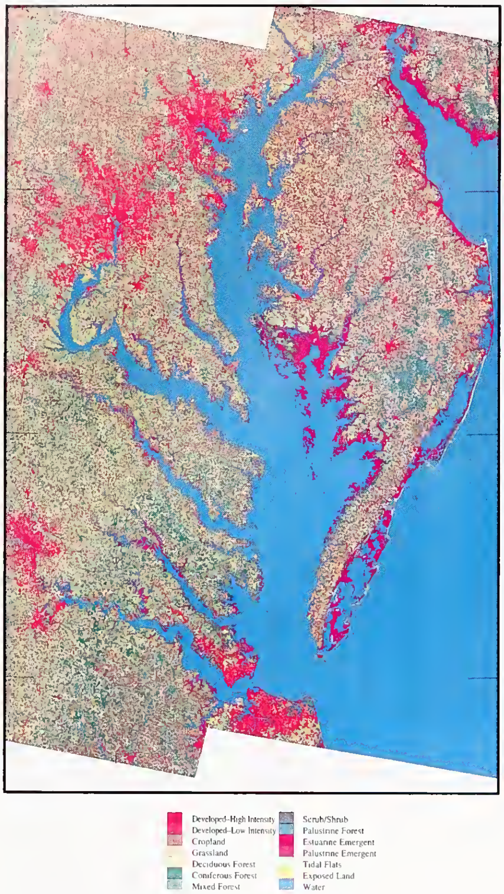
NOAA

CoastWatch satellite data are helping fisheries managers locate concentrations of endangered sea turtles off the North Carolina coast to minimize conflicts with the summer flounder fishery. Sea turtles are usually found in warm waters associated with winter Gulf Stream intrusions near the shore. Once these warm currents have been mapped using satellite data, airplane surveys follow to map turtle locations.

A National Program Maps Watershed and Habitat-Change Analysis

Recently, the general public has come to see what scientists have been saying for years—that while wetlands, especially coastal wetlands, are among Earth's most productive ecosystems, they continue to be filled, drained, or otherwise degraded. Loss of half the nation's coastal wetlands has eliminated breeding grounds for such commercially valuable species as shrimp, reduced the habitat that waterfowl and other wildlife require, made coastal waters more vulnerable to unfiltered, polluted runoff, and left coastlines unprotected from storms.

To preserve remaining resources, detailed data on the changes in important coastal habitats are needed. COP's Change Analysis Program (C-CAP) staff addresses this need by working with scientists and resource managers to develop a national protocol for mapping watersheds and habitats and detecting change through satellite and aircraft remote sensing. Through regional workshops, more than 200 scientists debated myriad issues to arrive at a unified, consistent approach to mapping land-cover data. This protocol will be used by federal agencies, states, and academic researchers to map coastal habitats and adjacent uplands so that habitat losses around the country can be consistently documented, compared, and analyzed. Intended to evolve as new technical issues are



NOAA/DOE/ORNL

C-CAP first applied its change analysis protocol to the Chesapeake Bay watershed to analyze changes in land cover and habitats for the nation's largest estuary. Completed in summer 1992, the Chesapeake Bay analysis illustrates the impacts of the rapid growth in the Washington, DC–Baltimore area, revealing a 1 percent loss in wetland habitats in the five years between 1984 and 1988/89.

confronted and resolved, the protocol will provide a practical tool for resource managers.

The standardized approach has already made a difference. With federal technical assistance, several states are beginning to explore their coastal habitats through satellite data and aerial photography. In North Carolina, C-CAP has helped the state map much of its submerged aquatic vegetation, giving resource managers information needed to protect these sensitive habitats from such disruptions as mechanical clam harvesting. With the success of this effort, the Environmental Protection Agency's Environmental Monitoring and Assessment Program (EMAP) is now cooperating with C-CAP to map submerged aquatic vegetation along the Gulf of Mexico coast. Florida's Department of Natural Resources is using satellite data to examine the impact of Hurricane Andrew on the Everglades mangrove forests. In 1992, C-CAP moved into the international arena, initiating a project to analyze changes in wetland and upland areas on both the US and Canadian sides of the St. Croix River estuary. Ultimately, C-CAP will work with states and regional organizations to map the entire US coast, and to analyze watershed and habitat changes every 1 to 5 years.

With the first stage of the protocol completed, C-CAP moves ahead to new challenges. Linking the mapped land-cover-change data with an improved understanding of how these habitats function is perhaps the most difficult, and the most crucial. In addition, COP has also funded studies to advance our understanding of how habitats, especially salt marshes and seagrasses, foster productive fisheries. These studies are essential for managing existing habitats and helping to recreate or restore damaged ecosystems. By supporting the development of models that explain the links between habitat functions and their spatial locations and extents, COP will provide fishery and other resource managers with the scientific tools needed to protect and rebuild the nation's coastal resources.

Nutrient Overenrichment Studies Began in the Gulf of Mexico

Excess nutrients—from sewage, agricultural and suburban runoff, and industrial waste—fertilize coastal waters, often with adverse effects. High nutrient loadings often cause algal blooms that decay in bottom waters, depleting them of oxygen (hypoxia) and harming benthic life. Overenrichment is an increasing problem in many coastal waters, yet the quantitative relationship between nutrient inputs, especially from nonpoint sources, and hypoxia is still poorly understood.

This problem is particularly important in the nation's largest water-

shed, the Mississippi River basin, which drains one-third of the continental US, including much of its agricultural lands. Nutrient-rich water flows into the Gulf of Mexico, resulting in algal blooms and hypoxic conditions that threaten the region's rich fishery resources. In 1989, COP's first field effort, the Nutrient Enhanced Coastal Ocean Productivity (NECOP) Program, was begun to study this problem. Sampling nutrient loadings at the Mississippi and Atchafalaya river outflows, NECOP researchers relate physical, chemical, biological, and geological observations to changes in primary productivity.

NECOP has demonstrated that extensive hypoxia along the Louisiana shelf is largely driven by nitrogen inputs from the Mississippi watershed. River nitrate concentrations have increased linearly with nitrogen fertilizer applications in recent decades, and models indicate that reducing nitrogen inputs will significantly reduce overenrichment in the Gulf of Mexico.

Measuring pollutant loadings from rivers and streams is relatively straightforward; from the atmosphere, it is more complicated. Yet a surprising portion of the nitrogen entering coastal waters stems from air pollution, primarily from auto emissions and power plants. In 1990, Congress amended the Clean Air Act to require NOAA and the Environmental Protection Agency (EPA) to determine the importance of the atmospheric pathway for hazardous air pollutants entering Chesapeake Bay and other water bodies. While previous studies had estimated that one-third of the nitrogen entering the bay came from the atmosphere, little was known about that assessment's accuracy, or the relative contributions of wet and dry deposition. COP's Atmospheric Nutrient Inputs to Coastal Areas (ANICA) project combines monitoring and modeling to quantify the contributions of both wet and dry nitrogen deposition, integrating deposition rates into atmospheric transport models. In addition to helping managers plan appropriate pollution-control strategies for Chesapeake Bay, ANICA is developing methods for assessing the importance of atmospheric input for other estuaries.

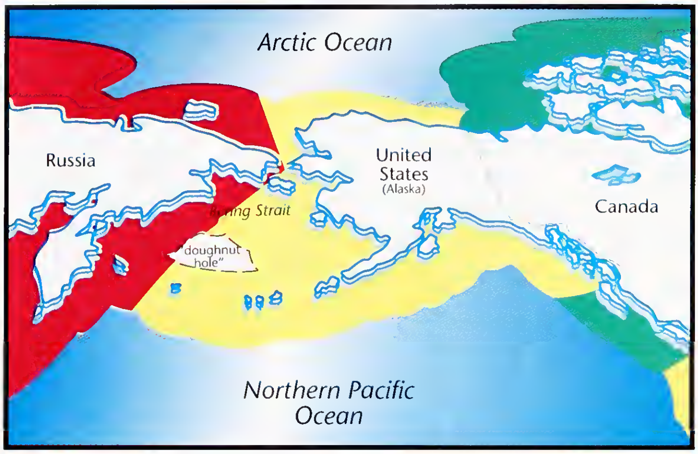
The nation's fish and shellfish resources are under siege.

Coastal Ecosystems Research: Helping a Diminished Industry

US fisheries are under siege. Overfished, losing valuable habitat, and subject to contamination from nutrient and toxic pollutants, the nation's fish and shellfish resources are increasingly threatened. Meanwhile, responding to the advice of health advocates, the individual American's consumption of fish has grown by 45 percent in the past 30 years. While other parts of COP's research program concentrate on the environmental quality and habitat needed to maintain healthy fisheries, the Coastal Fisheries Ecosystem (CFE) portion focuses directly on the ecological processes that affect commercial populations.

CFE grows out of a new direction in fisheries science, an integrated approach to understanding fisheries within the context of their ecosystems. The need for such an approach is clear. In the Bering Sea pollock fishery, for example, the largest single-species fishery in the world, the Russian and US 200-mile exclusive economic zones (EEZs) enclose a high-seas "doughnut hole" open to foreign fleets. Since the mid 1980s, this "hole," the central basin of the Bering Sea, has been heavily fished. The Northwest Fisheries Management Council needs to know how this

fishery affects stock sizes in the US EEZ. Recruitment, the number of adult fish added to the population each year, varies dramatically in pollock populations, creating enormous uncertainty in stock assessments. To improve these predictions, COP-funded scientists conduct genetic analyses of pollock stocks, to see how much stocks from foreign and US waters mix, and they mount field studies to determine what physical oceanographic and ecological factors affect pollock survival in the critical egg and larval periods. Once these factors have been identified, monitoring programs can be established to improve the scientific basis for pollock management.



E. Paul Oberlander/WHOI Graphics

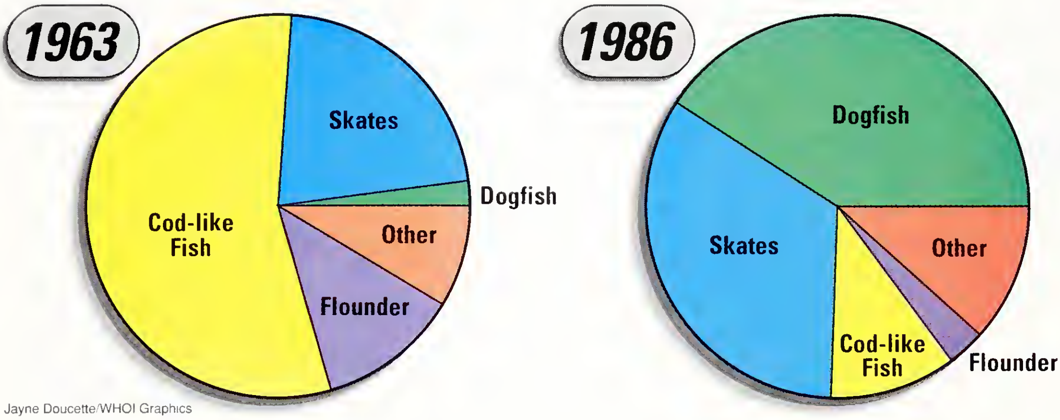
A "doughnut hole" exists within the US (yellow) and Russian (red) and near the Canadian (green) exclusive economic zones, allowing continuous open season for all nationalities in the Bering Sea pollock fishery. Investigators funded by the Coastal Ocean Program are studying this fishery to establish a scientific basis for managing it.

In the South Atlantic, COP-funded researchers are looking at a different recruitment problem: What determines the survival and growth of estuarine-dependent fish? Nationwide, about 75 percent of commercial fish species spend part of their lives in estuaries. In Atlantic menhaden, juveniles move into estuaries, presumably assisted by ocean currents, weeks after being spawned in the open ocean. After maturing in the estuaries for several months, the juveniles move offshore to mature and later spawn. Completing its first year, the South Atlantic Bight Recruitment Experiment (SABRE), based at Beaufort, North Carolina, is integrating information on offshore currents, salinity, temperature, and nutrients with seven years of data on migrating menhaden larvae to identify factors associated with recruitment peaks. By analyzing fish otoliths, tiny components of the inner ear that accumulate growth rings, investigators can determine the ages of sampled fish, and correlate strong year classes with particular environmental conditions identified by physical monitoring and satellite data.

Population models are also being used to determine how an individual fish's growth rate affects its chances of being eaten by predators. By modeling the factors that contribute to an individual's survival, SABRE scientists will identify key life stages that seem to control population size.

In 1993, COP will begin work on Georges Bank, which has sustained New England fishermen for generations. Today, the cod and flounder have been fished out, replaced by low-value dogfish and skates. These low-value species, which accounted for only a quarter of the catch (by weight) as recently as 1963, now make up 75 percent of the catch. COP's newest fishery project will focus on whether or not the species composition of this heavily stressed ecosystem can be restored. The Georges Bank effort will consider the effects of fishing and predation pressures on cod and flounder, and develop strategies to shift fishing pressure from the overexploited fisheries to the underutilized species.

In the meantime, fisheries managers must set annual catch limits and allocations based on the best information available. COP's ecosystem approach, while long term, will enable fisheries managers to understand



Jayne Doucette/WHOI Graphics

The composition of research vessel survey trawl catches on Georges Bank for 1963 and 1986 illustrate the dramatic change in the ecosystem structure.

many of the multiple influences on fish stocks. This should bring economic benefits that will help to close the nation's $3 billion trade deficit in fishery products.

Future Directions

As COP enters its fifth year, program participants are evaluating and disseminating completed research, and looking forward to strengthening NOAA/academic partnerships for work on persistent and emerging environmental issues. New areas of research, to meet new environmental challenges, are also underway. They include several approaches.

Developing a Coastal Forecast System. The National Weather Service's prediction of Hurricane Andrew saved lives, illustrating the importance of accurate storm and weather forecasts. Now, NOAA is developing a similar capability for the coastal marine environment. Among COP's new efforts is development of a Coastal Forecast System (CFS) for physical and biological conditions in the coastal ocean, including storms, circulation, and water quality. Made up of linked observation systems, research on coastal ocean processes, and models to integrate this information, the CFS will be a working prototype, updated as understanding of the systems advances and new technologies are developed. The CFS will integrate our knowledge of atmospheric, biological, and physical processes, and upgrade our ability to observe and predict them.

Protecting Environmental Quality. While the US has made great strides in controlling municipal and industrial pollution, the greatest remaining sources are now the most difficult to control. These "nonpoint" sources—agricultural and urban runoff, contaminants entering groundwater, and atmospheric deposition—include nutrients, toxic chemicals, and sediments. Building on experience in the Gulf of Mexico and Chesapeake Bay, COP coordinates a national research effort to predict the impacts of nutrient overenrichment on estuaries and coastal waters.

Another new area of COP-funded research is developing methods to assess the cumulative effects of development. Over the past 20 years, nearly half of new residential development has occurred in coastal counties. Yet managers have only recently recognized the importance of incremental changes that may lead to irreversible degradation. COP's groundbreaking effort will help managers protect water quality and sensitive habitats from this gradual encroachment.

Coordinating Federal Science Efforts. As federal and state budgets are squeezed, the need for cooperative scientific efforts is increasingly urgent. COP actively promotes such approaches, working through the Subcommittee on US Coastal Ocean Science (SUSCOS) created by the Federal Coordinating Council on Science, Engineering, and Technology under the president's science advisor. SUSCOS inventories federal spending on coastal ocean science and evaluates current programs against documented research needs. These findings—coordinated by COP, and completed in early 1993—will serve as the basis for a coordinated federal coastal ocean science strategy.

Coastal problems continue, often driven directly or indirectly by growing coastal zone populations. If the ecologic and economic costs of these problems are to be controlled, a stronger scientific understanding of coastal processes is essential. COP's scientific contribution—enhancing our understanding and predictions of the coastal environment—is a key ingredient for the sustainable development critical to our future use and enjoyment of the coast.

Lauren Wenzel served as a Sea Grant Fellow with the Coastal Ocean Program during 1992. She studied political science at Oberlin College and received an MS in Natural Resources Policy from the University of Michigan's School of Natural Resources and Environment. She is now intent upon building a career around frequent trips to the beach.

Donald Scavia is the Director of NOAA's Coastal Ocean Program. Prior to "dying and going administration," he spent 15 years researching and modeling Great Lakes nutrient cycles and plankton in Ann Arbor at the Great Lakes Environmental Research Laboratory as one of NOAA's freshwater oceanographers. He holds BS and MS degrees in Environmental Engineering from Rensselaer Polytechnic Institute and a Ph.D. in Water Resources Engineering from the University of Michigan. He spends most of his spare time carpooling his two daughters to early-morning swim practices.

Creative Camera Concepts/Ned Manter

Population growth and development are driving coastal environmental problems. In the 1980s, 45 percent of the US population lived in coastal counties such as Nantucket, Massachusetts. Coastal regions make up a mere 10 percent of US land area (excluding Alaska); if current trends continue, in the next 20 years this population will grow by 15 million to 127 million.

A Tale of Two Lighthouses

David M. Bush and Orrin H. Pilkey

America stands at a great crossroads with regard to shoreline policy. Many buildings on the East Coast beachfront are threatened by the Atlantic Ocean, or soon will be if current erosion rates continue. How we, as a society, should respond in the face of this impending doom is a matter of great controversy. The story of two lighthouses, Cape Hatteras Lighthouse in North Carolina and Morris Island Lighthouse in South Carolina, illustrates some of the complexities involved.

At 63 meters high, Cape Hatteras Lighthouse is the tallest brick lighthouse in the US, and one of the most famous. The present Cape Hatteras Lighthouse replaced

John F. Dunn

Ron Anton Rocz

Three groins help hold the shore in place at the Cape Hatteras Lighthouse (left). Today there is a noticeable bulge as the shorelines to the north and south have eroded. Morris Island Lighthouse (right), is presently some 500 meters offshore.

a shorter, dimmer, light built in 1803. Since 1870 it has warned mariners of the treacherous waters of Diamond Shoals that have earned North Carolina's Outer Banks the nickname "Graveyard of the Atlantic." Readily accessible by car, Cape Hatteras Lighthouse is today one of the East Coast's major tourist attractions. Morris Island Lighthouse, also known as Charleston Lighthouse, was first lit in 1876 and is about 50 meters high. Perhaps because Morris Island has always been inaccessible by car, it never became the tourist attraction that Cape Hatteras Lighthouse did, but it is a well-known local landmark for the important port city of Charleston. The present Morris Island Light replaced a pre-Revolutionary War light that was destroyed during the Civil War (by some accounts during the battle for Garrison Wagner that was made famous in the movie *Glory*).

How are the Cape Hatteras and Morris Island lights linked with respect to coastal policy? Cape Hatteras Lighthouse is in imminent danger of being destroyed by storm waves. It was originally built some 500 meters from the shore, but erosion has moved the shoreline to within 20 meters of the light. Morris Island Light has also been the victim of a rapidly retreating shoreline. To find it today, don't look on land or even near the shore, because it's *in* the water, some 500 meters offshore!

The Controversy

Controversy over whether or not to try to save Cape Hatteras Light, and if so, how, has raged since the 1930s. The arguments have strengthened since 1980, and are centered around whether to:

- armor the shoreline in an attempt to protect the lighthouse in place,
- relocate the lighthouse landward,
- replenish the beach, or
- do nothing, and let the lighthouse collapse when its time comes.

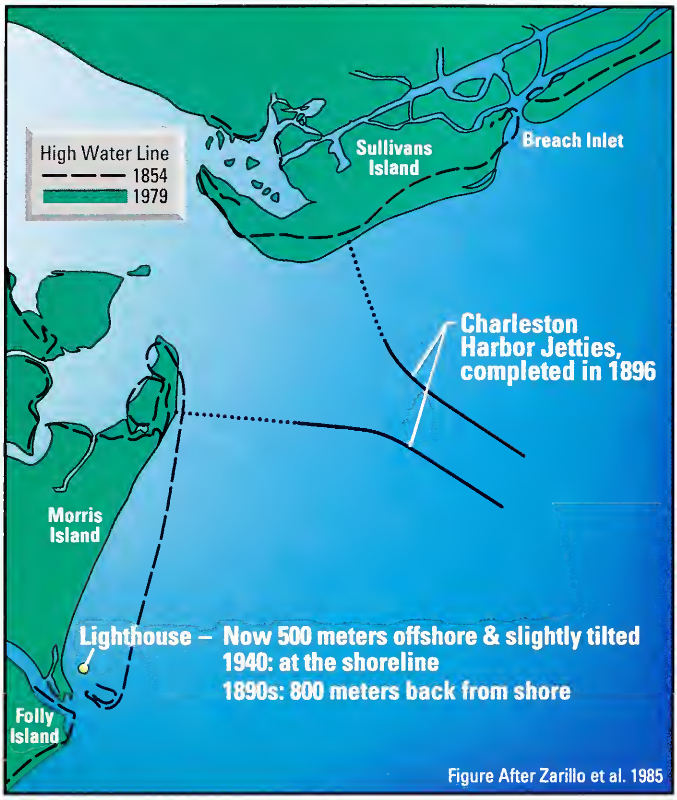
All sides have been steadfast, with impassioned arguments touting their different viewpoints. Many times it seemed likely the approaching shoreline would destroy Cape Hatteras Lighthouse before a decision could be reached about saving it! High erosion rates, high wave energy, and the lighthouse's vulnerability to hurricanes and other winter storms (such as nor'easters) meant time was of the essence.

In the 1930s shoreline migration brought the sea to within 30 meters of Cape Hatteras Lighthouse, and in 1936 the light was abandoned. By 1950 the shoreline had stabilized naturally. At this point, ownership was transferred from the US Coast Guard to the National Park Service, and Cape Hatteras Lighthouse was reactivated. In the 1960s and 1970s three groins were built, subsequently destroyed by a storm, and rebuilt. Nylon sandbags were emplaced in front of the lighthouse, and three other unsuccessful beach replenishment projects were also undertaken.

In 1980, a March storm washed away the remaining ruins of the original lighthouse and threatened the present Cape Hatteras Lighthouse. Quick thinking by the resourceful Park Service saved the light: They tore up the parking lot and placed the rubble in front of the light to protect it from the storm. In 1981, the National Park Service asked the US Army Corps of Engineers for their evaluation. In 1985, the National Park Service decided that protecting the lighthouse in place with a massive seawall was the best way to save it. Under pressure from local opponents of shoreline armoring, however, they decided to reconsider the options, and in 1987 they asked the National Research Council for help. A Research Council committee concluded that relocation was the best option. As of this writing, the National Park Service is pursuing relocation of the lighthouse.

Morris Island Lighthouse was never surrounded by such controversy. The light has been along the beach or offshore since the late 1930s, so perhaps no one thought of it in terms of needing to be "saved." When Morris Island Light survived a direct hit from Hurricane Hugo in 1989, it was reported that Cape Hatteras Light could also survive a major storm in place, and therefore relocation was not required to save it. In addition, many reckoned that relocating such structures did not necessarily set a good precedent for coastal zone management philosophy.

Comparing these two lighthouses and saying that what is good for the goose is good for the gander is an



Jayne Doucette/WHOI Graphics

Morris Island Lighthouse and the Charleston Jetties. The jetties were built in the late 1800s when the lighthouse was still some 800 meters inland. With the jetties cutting off the natural sand transport, starving Morris Island of sand, the shoreline began to rapidly erode and by 1940 had eroded back to the lighthouse.

oversimplification of the problem. Cape Hatteras Lighthouse and Morris Island Lighthouse differ in several ways and need to be considered separately.

The Coastal Physical Setting— More than Meets the Eye

Cape Hatteras Lighthouse is in a more dangerous physical location than Morris Island Lighthouse. Cape Hatteras juts out into the Atlantic, and somehow seems to attract winter storms and hurricanes, while Morris Island is somewhat sheltered by sand shoals. The continental shelf is narrow off Cape Hatteras and wide off Charleston, which has a profound effect on overall wave energy, tidal range, and the maximum potential storm surge. Mean wave heights are relatively high off Cape Hatteras, and low off Charleston, yet the tidal range distribution (the mean water height, between successive high and low tides) is exactly the opposite. The bottom line is that there is greater potential for wave damage at Cape Hatteras Lighthouse than at Morris Island Lighthouse, but the potential maximum storm surges at Morris Island are higher than at Cape Hatteras.

Much is made in news reports about the dangerous combination of a hurricane making landfall at high tide. That is precisely what occurred during Hurricane Hugo when a 4-plus-meter storm surge was added to a 1.5-meter astronomical high tide. In low tidal-range settings, such as Cape Hatteras, low water levels are not significantly different from high water levels. No matter what point during the tidal cycle a hurricane hits, it will always be near mean water level. On the other hand, in high tidal-range settings, such as Morris Island, there is a significant quantitative difference between high and low water levels. If a storm happens to hit during maximum low water, the storm's impact will actually be lessened.

The erosion histories of the two locations also differ. Morris Island's shoreline has essentially been moving straight back. Cape Hatteras, however, has been fluctuating back and forth, although over the long term, the shoreline has moved back as well. This difference may be attributed to the differences between a cape and a barrier island.

The Shoreline Engineering Setting is Vitally Important

Cape Hatteras is not a highly engineered shoreline. An artificial dune was built along a large portion of the Outer Banks shoreline in the 1930s. Other than the beach replenishment projects and groins mentioned, the shore is unstabilized. Morris Island,

however, sits in the sand-transport "shadow" of the Charleston Harbor jetties, and is greatly affected by shoreline engineering. The jetties interrupt the predominantly southward transport of sand along the shore, resulting in severe erosion south of the jetties.

The Cape Hatteras shoreline is being held in place by the groins that have also likely protected Cape Hatteras Lighthouse so far. Meanwhile, Morris Island is being destroyed by the jetties.

Lighthouse Design Differences

The foundation of Cape Hatteras Lighthouse is only about 2 meters thick, consisting of granite rubble and masonry laid on top of two courses of yellow pine. The foundation's base is about .3 meters above sea level, and the lighthouse extends about 63.4 meters from there. Except for a wall of large nylon sandbags partially encircling the base, the lighthouse foundation is not armored, leaving it vulnerable to storm-wave scouring and destruction via undermining and toppling.

The base of the foundation of Morris Island Lighthouse is below sea level, and is far more substantial than that of Cape Hatteras Lighthouse. Morris Island Lighthouse's 2.5-meter-thick concrete foundation sits atop piles driven up to 15 meters deep and overlain by two courses of timber encased in concrete. Beyond this, the lighthouse extends 50 meters. To protect against damage from the extreme erosion rates common to this region, the base of the lighthouse was strengthened in 1938 with a sheet pile cylindrical wall with a concrete cap. Morris Island Lighthouse's base is obviously much better protected from wave scour than is Cape Hatteras Lighthouse's, and is therefore much more likely to withstand the fury of storm waves.

Forging Shoreline Policies is Complicated

The Cape Hatteras and Morris Island lighthouses differ in several important ways. Cape Hatteras has higher wave energies, erosion that is often unpredictable in the short term yet severe in the long term, and lower tidal range, meaning maximum storm surges will always occur. It is protected by relatively modest shoreline engineering, and has a shallow, unprotected foundation. Morris Island has a relatively low wave climate, a high erosion rate, and a high tidal range, which can increase or decrease a storm's impact depending on when the storm hits. It is severely affected by erosion caused by the Charleston Harbor jetties, and has a deep, highly engineered foundation that is armored against wave scour.

Coastal-zone managers must take into account all the differences: physical, geomorphic, engineering, and political, when devising shoreline policy. The future is bright for these kinds of considerations, mostly because the past is so dark. Small steps are being made in the right direction. Several states are banning seawalls, and South Carolina has begun a 40-plus year process of removing seawalls from its beaches. On a national level, the US Congress is considering including erosion rates and erosion zones as part of the National Flood Insurance Program (NFIP), restricting building in high-erosion-rate zones. Revision of relocation provisions in the Upton-Jones Amendment to NFIP to pay for relocation of large structures such as condominiums and hotels is being considered. ✪

David Bush was deeply involved with the Cape Hatteras Lighthouse controversy as a member of the "Move the Lighthouse Committee," so is biased toward relocation as a viable coastal management alternative. He finds it hard to leave Duke University where he received his Ph.D. in geology, and continues there as a Research Associate in the Program for the Study of Developed Shorelines.

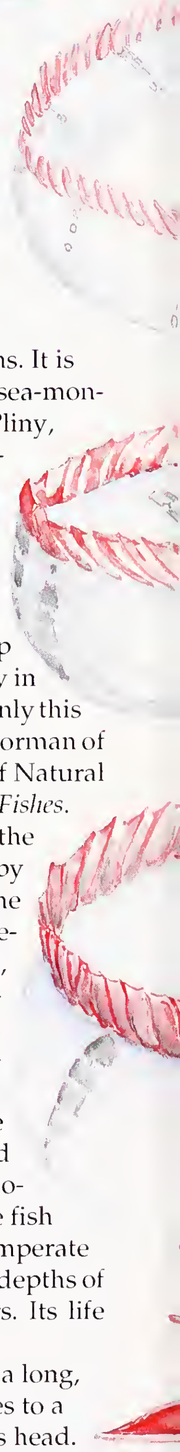
After 15 years of researching deep-ocean sedimentation, Orrin Pilkey realized that at cocktail parties people would listen more attentively when he talked about coastal erosion, hurricanes, and shoreline processes than about turbidity currents and abyssal plains. He subsequently stopped going on deep-sea research cruises and started going to the beach. For over 25 years he has plied his trade on the faculty of Duke University where he is James B. Duke Professor of Geology and Director of the Program for the Study of Developed Shorelines.

Creature Feature

The Oarfish

"Sea Serpent" Remains Mystery of Science

Cheryl Lyn Dybas



Sometime after nightfall on September 24, 1963, an 18-foot-long sea creature washed ashore near Malibu, California. Around midnight, Malibu resident Carole Richards took her poodle for a walk along the beach, happened upon the creature's huge body, and screamed in terror. Phyllis Huggins, a neighbor, heard her cry, and within minutes lights flashed on in houses throughout Malibu as word spread that a "sea serpent" lay dead just outside.

According to a police report of the incident, a passerby named North Young bravely dragged the monster off the beach and laid it across the top of his car, intending to take it to local authorities. Young had driven less than a mile from the beach when two police deputies spotted his vehicle, did a double-take, turned their squad car around, and directed its headlights at "a gigantic creature draped across a car roof." The officers quickly decided they'd better "call in the experts on this one."

"And that's how I came to be at the scene," remembers Boyd Walker, now emeritus professor of zoology at the University of California, Los Angeles. "Vlad Walters, another zoologist at the university, and I jumped into a truck, roared out to Malibu, and brought the dead 'sea serpent' back to the lab for analysis. Far from being a fearsome monster of the deeps, however, it turned out to be one of the rarest and most beautiful fish in the sea—an oarfish, *Regalecus glesne*." The oarfish specimen is now on display at the Los Angeles County Museum of Natural History. According to fish curator Robert Lavenberg, it's an almost complete animal—a rare find—except for a meter or so of its tail, which was probably bitten off by sharks.

With its eerie, sinuous silhouette, it's little wonder that the oarfish has long been mistaken for a sea serpent. Indeed, those who study the fish say that a person who reports seeing a creature with all the characteristics of an oarfish might well be suspected of having hallucinations. It is now thought that the sea-monster tales of Aristotle, Pliny, and other classical observers were likely accounts of oarfish sightings. "Even the famous Sea Serpent, measuring fifty-six feet in length, cast up on the shore of Orkney in 1808 was almost certainly this fish," maintains J.R. Norman of the British Museum of Natural History in *A History of Fishes*.

Called "king of the palace under the sea" by Japanese fishermen, the oarfish is the longest teleost (that is, bony, rather than cartilaginous, fish) in the ocean. A member of the family Regalecidae, it may reach lengths of more than 17 meters and weigh up to 300 kilograms. The serpentine fish is found in warm, temperate waters worldwide, at depths of from 20 to 200 meters. Its life span is unknown.

An oarfish sports a long, red dorsal fin that rises to a manelike crest atop its head.

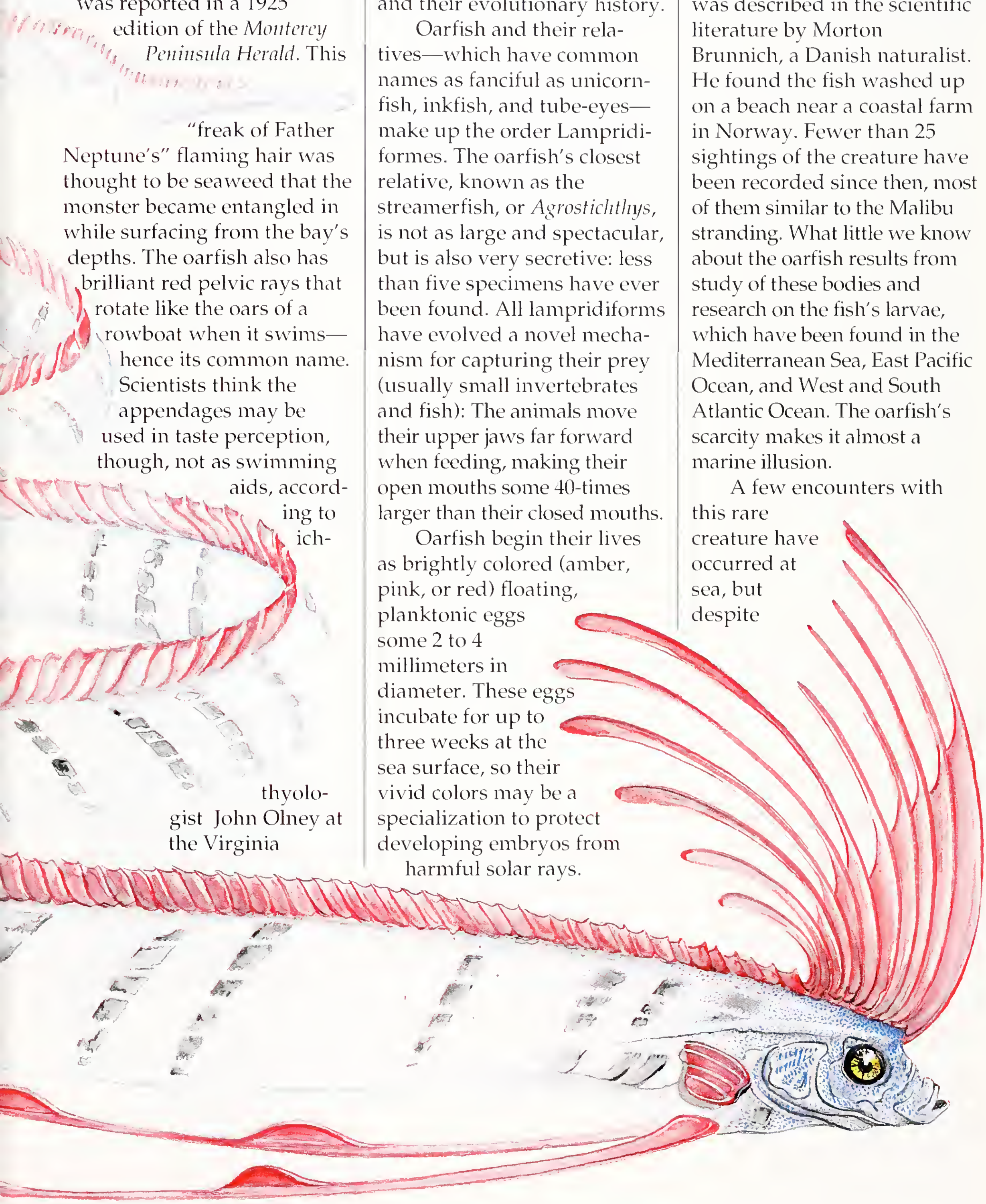
A "sea monster with fiery red hair," glimpsed undulating through the deep waters of California's Monterey Bay, was reported in a 1925 edition of the *Monterey Peninsula Herald*. This "freak of Father Neptune's" flaming hair was thought to be seaweed that the monster became entangled in while surfacing from the bay's depths. The oarfish also has brilliant red pelvic rays that rotate like the oars of a rowboat when it swims—hence its common name. Scientists think the appendages may be used in taste perception, though, not as swimming aids, according to ichthyologist John Olney at the Virginia Institute of Marine Science in Gloucester Point. Olney is one of the few marine biologists who currently study oarfish and their evolutionary history.

Oarfish and their relatives—which have common names as fanciful as unicornfish, inkfish, and tube-eyes—make up the order Lampridiformes. The oarfish's closest relative, known as the streamerfish, or *Agrostichthys*, is not as large and spectacular, but is also very secretive: less than five specimens have ever been found. All lampridiforms have evolved a novel mechanism for capturing their prey (usually small invertebrates and fish): The animals move their upper jaws far forward when feeding, making their open mouths some 40-times larger than their closed mouths.

Oarfish begin their lives as brightly colored (amber, pink, or red) floating, planktonic eggs some 2 to 4 millimeters in diameter. These eggs incubate for up to three weeks at the sea surface, so their vivid colors may be a specialization to protect developing embryos from harmful solar rays.

Ichthyologists understand little more about the oarfish's habits now than they did in 1771, when the first specimen was described in the scientific literature by Morton Brunnich, a Danish naturalist. He found the fish washed up on a beach near a coastal farm in Norway. Fewer than 25 sightings of the creature have been recorded since then, most of them similar to the Malibu stranding. What little we know about the oarfish results from study of these bodies and research on the fish's larvae, which have been found in the Mediterranean Sea, East Pacific Ocean, and West and South Atlantic Ocean. The oarfish's scarcity makes it almost a marine illusion.

A few encounters with this rare creature have occurred at sea, but despite



attempts to lure it close enough to a ship to be caught, none has succeeded.

A 1906 encounter may be the closest scientists have come to capturing a live adult *Regalecus*. Marine biologist F. Wood Jones published an account of the sighting in *The Fishes of the Indo-Australian Archipelago*. On October 28, some 30 miles south of the Island of Sumbawa, a "long and very beautiful fish came to the surface at the ship's bow. Baited rigs were thrown to it, but it took no notice of them." Although the vessel's crew wasn't able to entice the oarfish onto a hook, Jones says that in the water, the fish was a wonderful sight: "With its vivid red crest and dorsal fin, scarlet streamers on its sides, and blue of its head and intense shine of silver on its body, it was probably the most beautiful creature I've ever seen."

Naturalist C.F. Holder is one of the few other scientists to have seen an adult oarfish alive. In 1925, Holder chanced upon a small oarfish swimming in shallow waters along the beach of Avalon Bay on Santa Catalina Island, off southern California. "The opportunity to observe this radiant creature was one I'll never forget," he wrote in *Fishes*. "The fish was a fragile and delicate creature, a very ghost of a fish, which swam along just beyond where the water gently lapped the sands. It was a striking creature, showing naught but a vivid red mass of seeming plumes and a silver sheen where it undulated through the water."

Oarfish from more recent "sea serpent encounters" along the coast of California—five, in fact—can be found in the fish collection of the Scripps Institution of Oceanography in La Jolla, California, according to Richard Rosenblatt, curator of fishes. The most recent specimen (1986) died when it became trapped in a fisherman's driftnet near the San Juan seamount in the Eastern Pacific; a warning, perhaps, of more such "catches" to come.

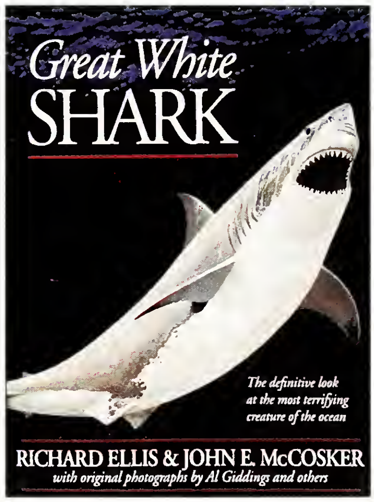
"The oarfish has but blundered into the hands of man in the past," said the late Romeo Mansuetti, a biologist at the University of Maryland Chesapeake Biological Laboratory at Solomons Island. "As he plies the ocean in ever greater numbers, man's encounters with the oarfish may—or may not—increase. In any case, may it be remembered that the fish has no commercial value, nor any potential as a game fish." In spite of increasing exploration and exploitation of the oceans, John Olney believes that because of the oarfish's rarity, the secrets of its life may never be fully revealed. But if such a fish can even exist, there may be all sorts of creatures in the sea's depths that we know nothing about.

Cheryl Lyn Dybas specializes in writing about "underappreciated" creatures of the deep. Her articles on marine life have also appeared in National Wildlife, International Wildlife, Wildlife Conservation, *and the National Science Foundation's* Directions *magazines.*

Book Review

Great White Shark

By Richard Ellis and John E. McCosker, 1991. HarperCollins Publishers, in collaboration with Stanford University Press, New York, NY; 270 pp. - $50.



This folio-size volume, profusely illustrated with reproductions of old photographs and paintings, excellent color photographs by Al Giddings and others, as well as the handsome paintings of Richard Ellis, provides the general reader with a rich background of information about one of the most awesome fish in the sea—the Great White Shark, *Carcharodon carcharias*. This much maligned and controversial predator is so rarely seen today that many fear it is destined for extinction unless effective measures for its protection are adopted. And therein lies the paradox; in the 1950s to 1970s, we were concerned about protecting

humans from sharks—today, because of overfishing and the shark's low reproductive rate, we are concerned about protecting sharks from humans—and the Great White Shark is number one on the list of endangered fish.

The 12 chapters of this entertaining volume cover a wealth of information on *Carcharodon*–much of it admittedly gleaned from the literature, because opportunities to see this great fish alive, or work with it experimentally in captivity, are very limited. Both Ellis and McCosker have observed *Carcharodon* in its native waters and have been impressed with its great power and majestic appearance.

Following the introduction, the authors put *Carcharodon* in perspective with its close and distant relatives. An ancient relative, *Carcharodon megalodon*, is believed to have reached a length of 50 feet and weighed 20 tons. Today, only its fossil teeth remain to testify to its size and presence in the Miocene era, 15 to 20 million years ago.

Subsequent chapters discuss the present Great White Shark's size (up to 21 feet long), its anatomy, physiology, and reproduction, revealing an array of fascinating facts. For example, it is believed to be one of the few fish able to elevate its body temperature as much as 5° to 7° Fahrenheit above that of the ambient water; it gives birth to few offspring every other year and is probably oophagus: the first developing pups probably devour their siblings in utero; and as for its food and feeding, in 1982, Francis G. Carey estimated it can survive for 45 days on as little as 66 pounds of whale meat.

Very few Great White Sharks have ever been kept in captivity and none has survived very long. A 13-footer was displayed in Hawaii's Marineland in 1961 and lived only 24 hours. An 8-foot male Great White displayed in 1962 in Marineland (Florida) lived 36 hours, and a 7.5-foot youngster was kept in the California Steinhart Aquarium for three and one-half days before it was released off the Farralon Islands, 26 miles at sea.

The Great White primarily frequents temperate waters, and those worldwide locations are well-depicted in map form in *Great White Shark*. Naturally, the Great Whites seem to prefer places where seals, sea lions, and fur seals abound—as in the waters of South Africa, New Zealand, South Australia, and off the coasts of Chile and central California.

Chapter 8 deals with Great White Shark attacks on humans, which for all the publicity they receive, are relatively rare. Only 60

documented cases are recorded, 16 of which were fatal. Other predatory sharks, including the oceanic whitetip *Carcharhinus longimanus*, the bull shark *Carcharhinus leucas*, and the tiger shark *Galeocerdo cuvier*, are probably more often the culprit in attacks on humans than the Great White. For those who are still timid about going to sea because of memories of the movie *Jaws*, this book should go far to allay their fears. And, for those who admire the majesty and power of the Great White Shark, this volume will reinforce their desire to protect and preserve it.

Opportunities to observe this impressive fish in captivity or in its native waters are now rare indeed. This leads the authors to conclude, "...if this book has a purpose beyond exposition, explanation, and entertainment, it is to make very clear the plight of this great fish...[for] it may be in danger of disappearing forever." ✪

—Perry W. Gilbert
Director Emeritus
Mote Marine Laboratory
and Professor Emeritus
Cornell University

If you'd like to know more...

A list of additional readings for the topics discussed in this issue of Oceanus is available!

Call Justine Gardner-Smith at 508-457-2000, ext. 2388 to request a list.

COMING UP NEXT...

Coastal Science & Policy II

Volume 36, Number 2, Summer 1993

Cynthia R. Cronig

If you've found this issue's look at coastal science and policy interesting, you can look forward to more near- and onshore articles in our next issue. Scientists will provide the latest information on estuaries, rivers, and coastal wetlands, and a fisheries biologist will discuss the current status of an important food source, marine fisheries. Coastal pollution and the use of mussels to monitor coastal waters' health will be featured along with the US Navy's new view of coastal science. We'll offer a profile of David Packard and Julie Packard, principals in the Monterey Bay Aquarium and Research Institute, and there'll be a behind-the-scenes discussion of US ocean science policy formulation. Please join us for this wide-ranging *Oceanus* issue on coastal science and policy!

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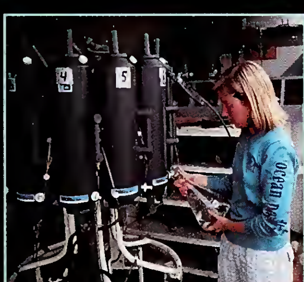
R/V *Cape Hatteras*

Photos by Scott D. Taylor, Duke Marine Lab



The Research Vessel *Cape Hatteras* is designed for coastal as well as open-ocean research. The 41-meter ship is operated by the Duke University/University of North Carolina Oceanographic Consortium. As its 46-cruise schedule for 1993 attests, *Cape Hatteras* offers a versatile platform that can accommodate a wide range of oceanographic studies. For the first four months of 1993, the ship was based in Bermuda for operations that ranged from deploying moorings and benthic landers to hydrographic stations for the Joint Global Ocean Flux Study. On the one- to fourteen-day cruises planned for the rest of the year, studies include extensive work on various aspects of the continental-rise sediments and on phytoplankton communities that live along the North Carolina coast. Research on Sargasso Sea zooplankton and electromagnetic equipment testing are among other investigations on the ship's schedule. *Cape Hatteras* and its sister ship *Point Sur*, operated by Moss Landing Marine Laboratories, were constructed with National Science Foundation funds in 1981. Each accommodates a 12-member scientific party.